

Title: Calculating Radiological Exposures in Dense Urban Areas:
Linking a Building-Aware Atmospheric Dispersion Model with
a Radiological Transport Model

Author(s): Matthew A. Nelson, J. Timothy Goorley,
and Michael J. Brown

Intended for:



Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the Los Alamos National Security, LLC for the National Nuclear Security Administration of the U.S. Department of Energy under contract DE-AC52-06NA25396. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

Calculating Radiological Exposures in Dense Urban Areas: Linking a Building-Aware Atmospheric Dispersion Model with a Radiological Transport Model

**Matthew A. Nelson, J. Timothy Goorley,
and Michael J. Brown**

Los Alamos National Laboratory

LA-UR-11-04176

Introduction

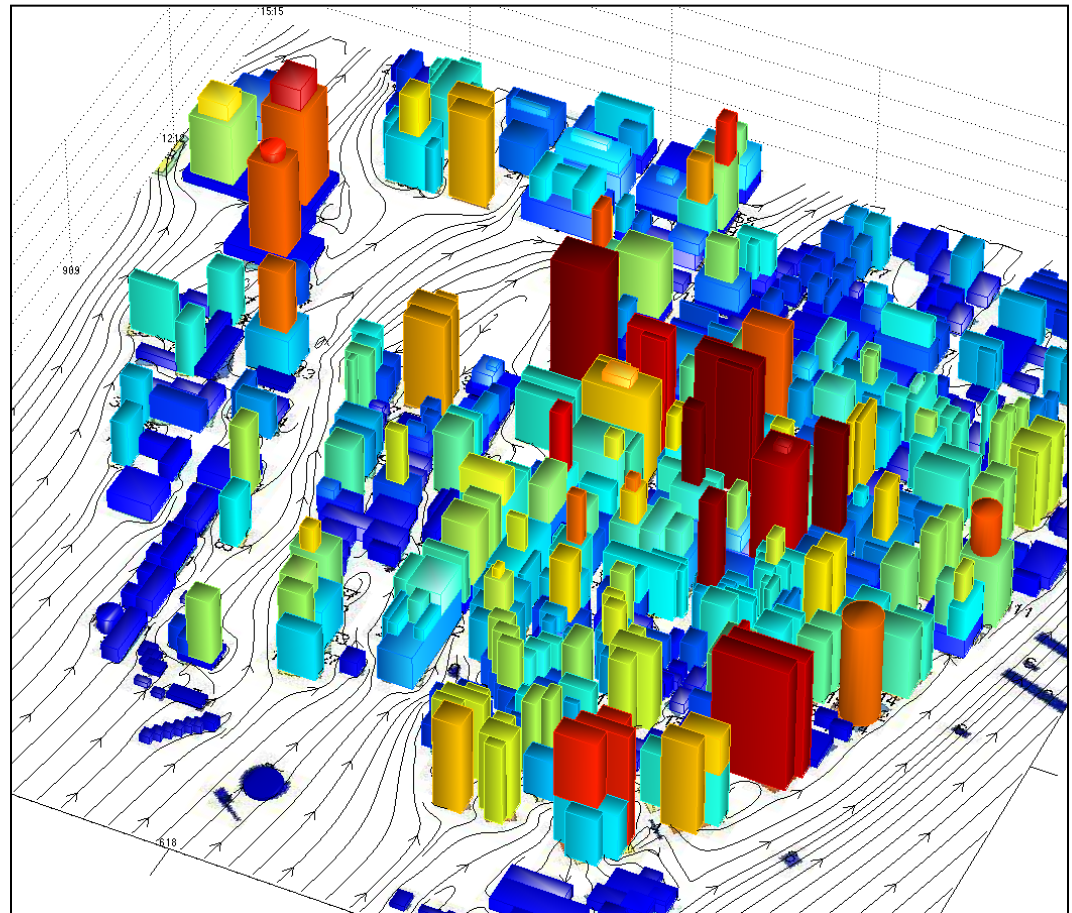
- **What is QUIC?**
- **QUIC's Capabilities**
- **MCNP**
- **Times Square RDD Simulation**
- **Exposure Calculations**

What is QUIC?

**Quick Urban & Industrial Complex
dispersion modeling system**

* QUIC-URB

produces 3D wind field
around buildings using
empirical/diagnostic model
based on Röckle (1990)



UNCLASSIFIED

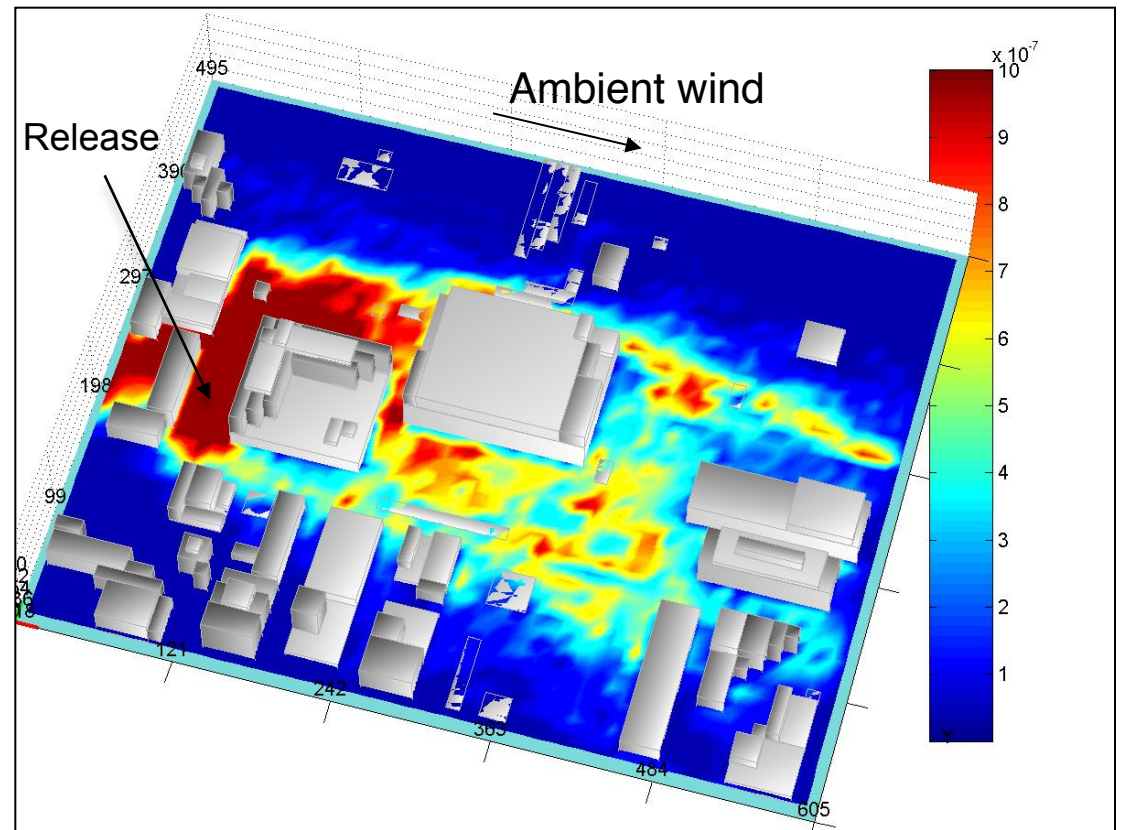
Lower Manhattan

What is QUIC?

**Quick Urban & Industrial Complex
dispersion modeling system**

* QUIC-PLUME

accounts for building-
induced turbulence
through Lagrangian
random-walk dispersion
model



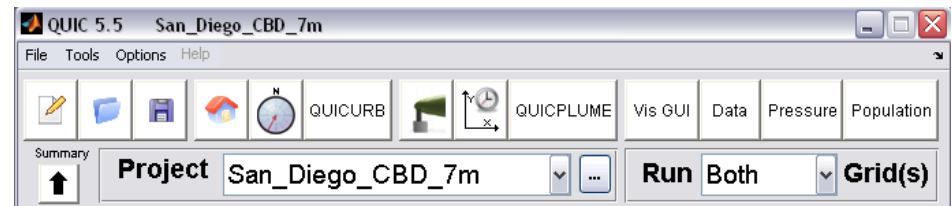
Boston Convention Center

What is QUIC?

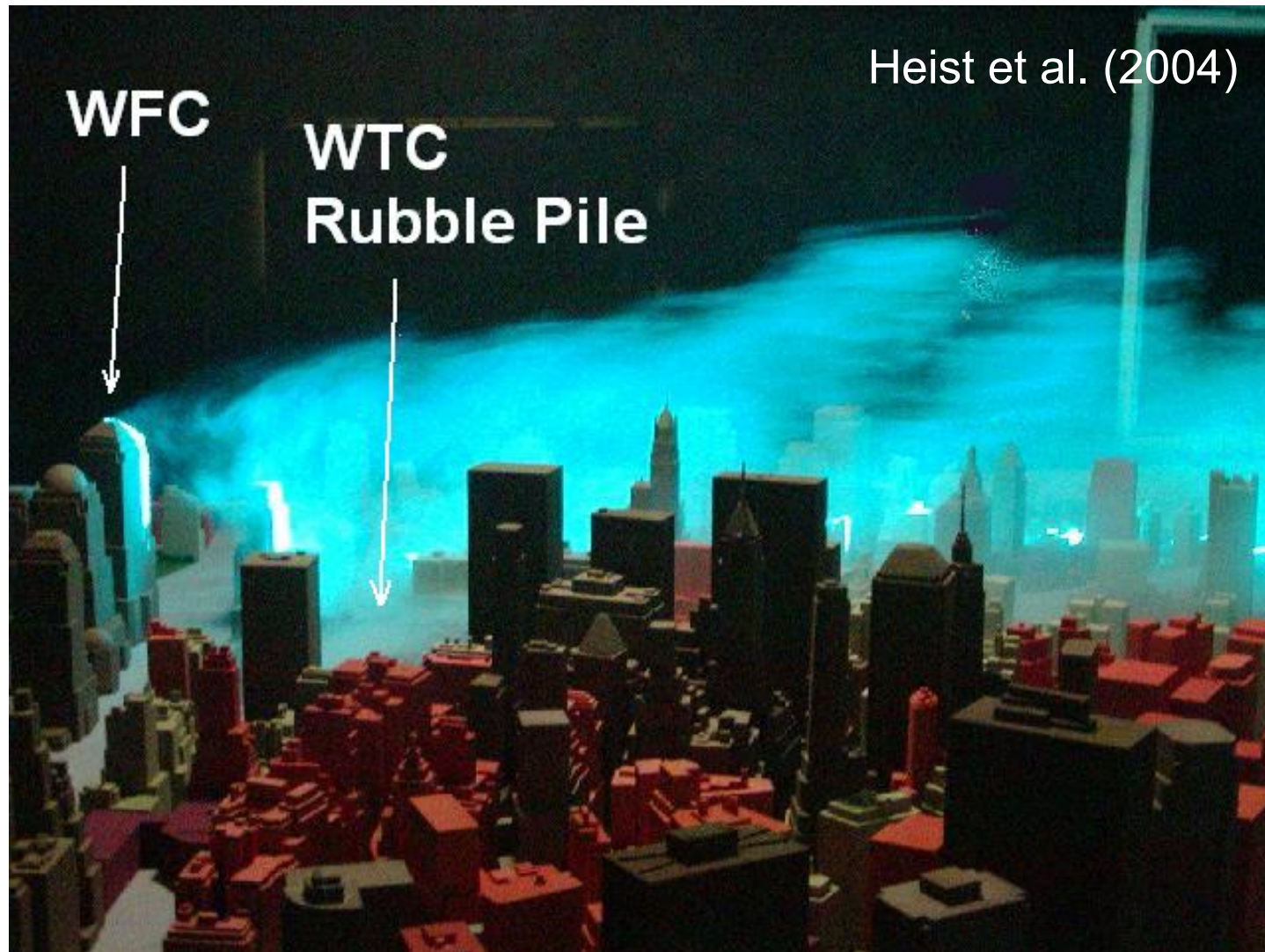
**Quick Urban & Industrial Complex
dispersion modeling system**

* QUIC-GUI

graphical user interface for set-up,
running, and visualization

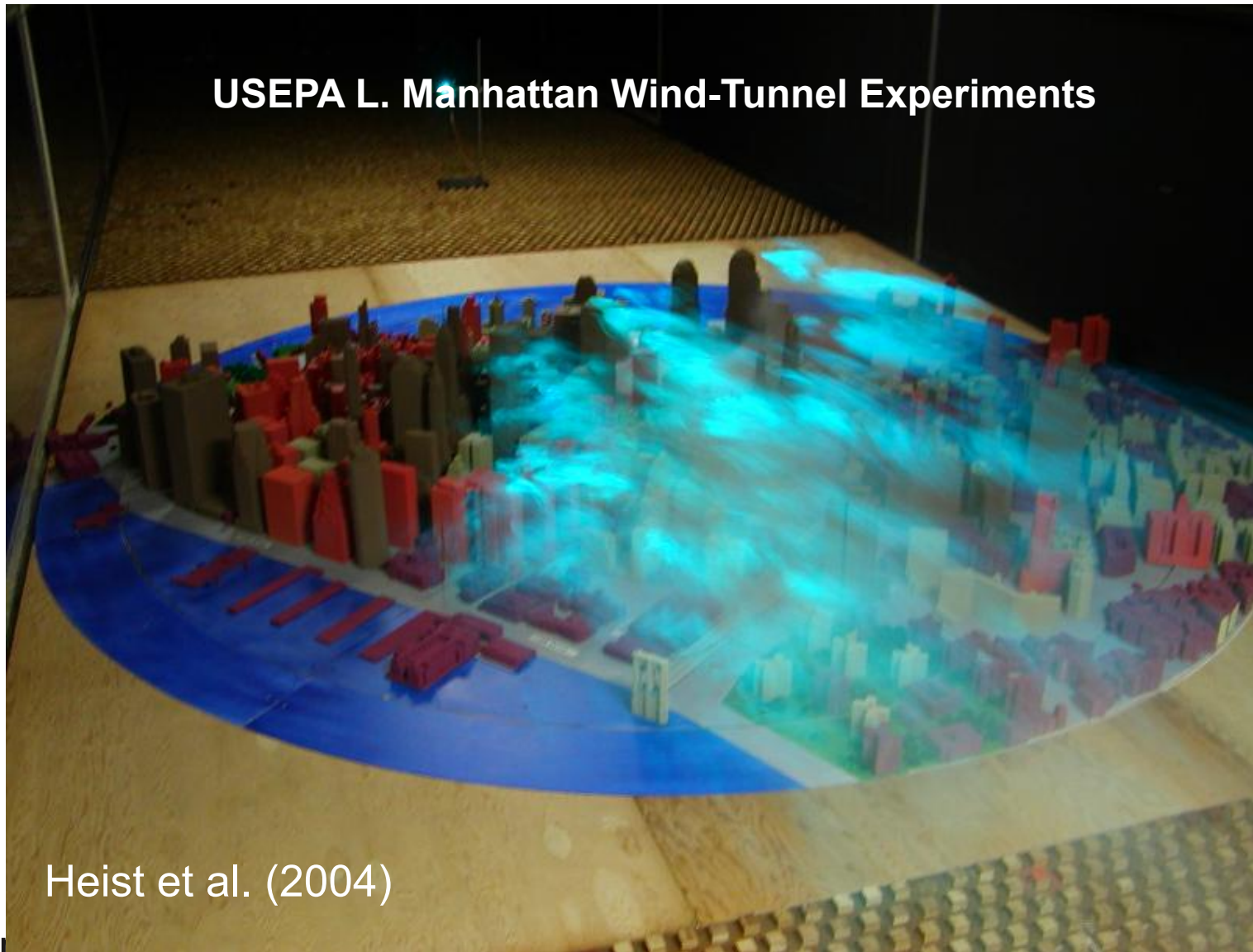


Impact of Buildings on T&D



Impact of Buildings on T&D

USEPA L. Manhattan Wind-Tunnel Experiments

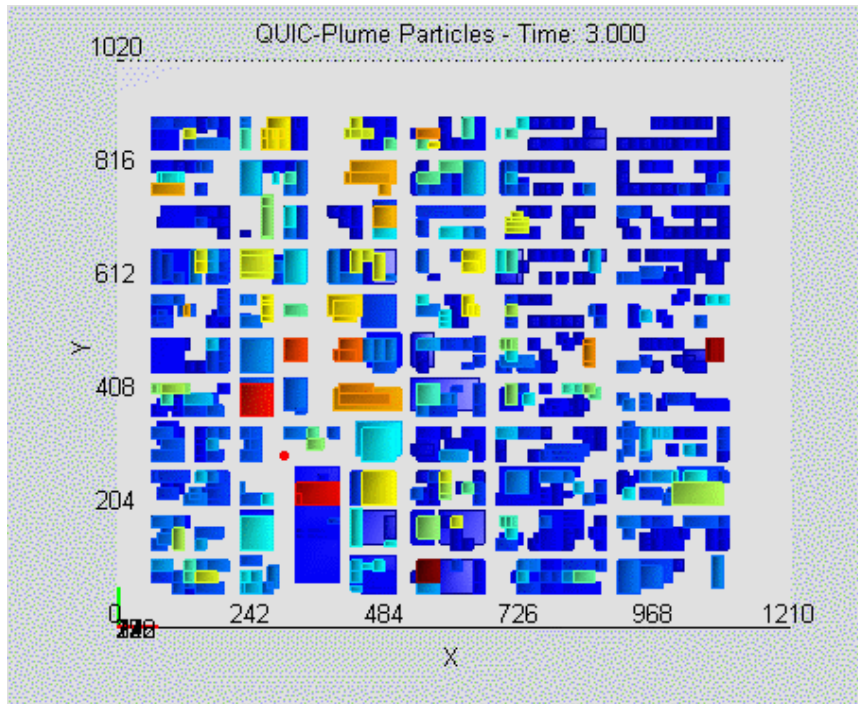


Heist et al. (2004)

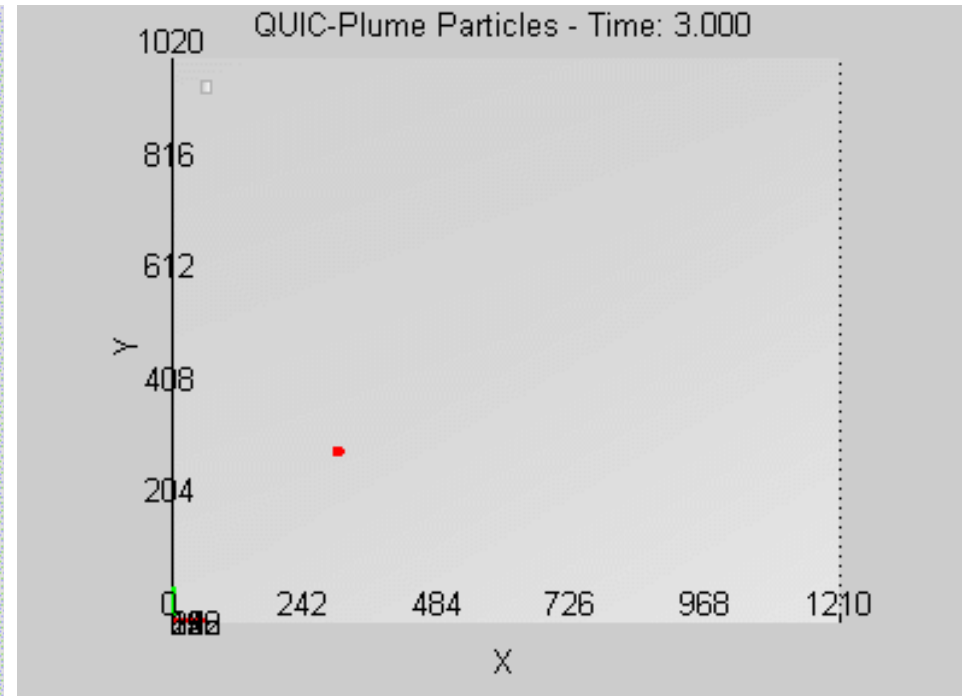
Impact of Buildings on T&D

Impact of buildings on retention and timing

Midtown @ Grand Central Station – Particle dispersion animation



QUIC model w/ buildings



QUIC model w/out buildings

Release Type

Dense Gas Releases



Instantaneous Source Representation

$$Volume_{cyl} = \frac{Q}{\rho_{dg}}$$

$$Volume_{cylinder} = \pi \cdot r^2 \cdot h$$

$$r = \sqrt{\frac{Q}{\rho_{dg} \pi h}}$$

User specifies: h , Q , & ρ_{dg}
QUIC calculates r and uniformly distributes Lagrangian markers within a cylinder



Cloud Movement

Track movement of expanding dense gas cloud

Cloud velocity based on volume average of wind field inside cloud



Dense Gas Outflow Velocities

Any particles inside the cloud behave as dense gas, particles outside are neutrally buoyant

Outward buoyancy-driven velocity



$$\bar{v}_{dg} = \frac{dR}{dt} \frac{r_s}{R}$$

R = radius of cloud
 r_s = distance from center of cloud

Cloud Growth Rate



$$\frac{dR}{dt} = \frac{1}{R} \sqrt{g \frac{\rho_{dg} - \rho_a}{\rho_a} Vol_0}$$

$$\Delta Vol = (\pi R^2) (0.65 u_{dg}) \Delta t + (2 \pi R h) (0.7 \frac{dR}{dt}) \Delta t$$

$$h = \frac{Vol}{\pi R^2}$$

↑ entrainment thru top
↑ entrainment thru sides

From Hanna and Drivas (1987)

Turbulence Damping

$$u_{dg} = \frac{u_s}{(1 + 0.2 \cdot Ri_H)}$$

$$\sigma_{u_{dg}} = \sigma_{u_s} \frac{u_{dg}}{u_s}$$

where $Ri_H = \frac{g h (\rho_{dg} - \rho_a)}{\rho_a u_s^2}$

Small random vertical perturbations added to keep particles well-mixed within dense cloud

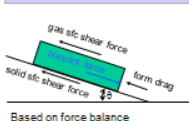
From Briggs, Britter, Hanna, Havens, Robins, and Snyder (2001)

Effect of Buildings



Compute an "effective" radius based on volume occupied by buildings

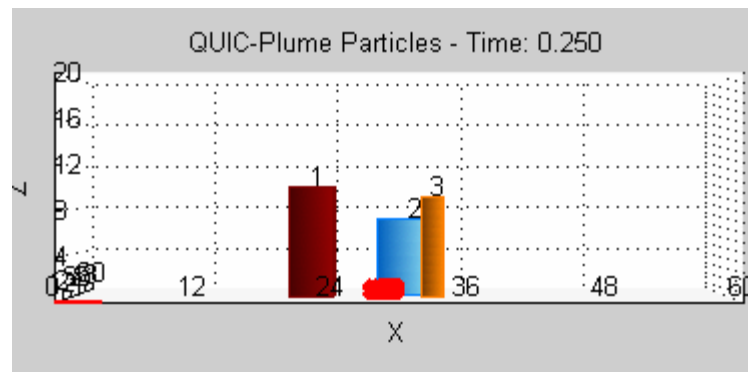
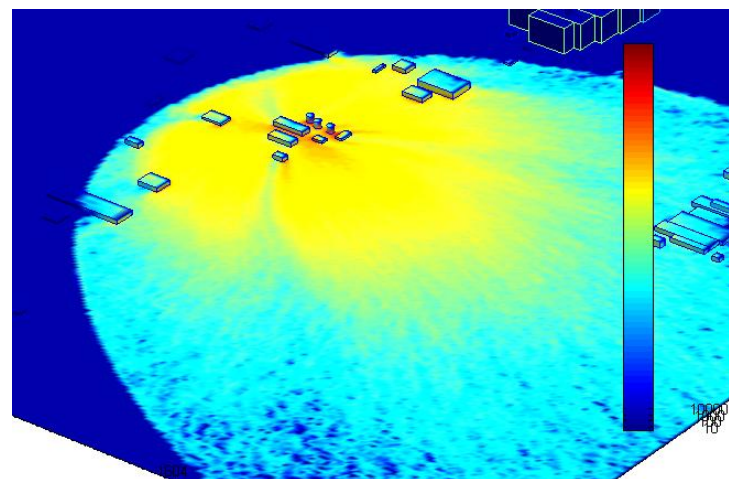
Effect of Topography



Based on force balance

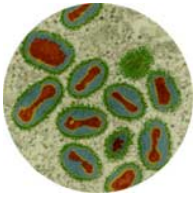
$$v = \left[\frac{g \frac{\rho_{dg} - \rho_a}{\rho_a} H \sin \theta}{2 \frac{\rho_a}{\rho_{dg}} \left(\frac{u}{v} \right) + \frac{H}{\pi R} C_D} \right]^{1/2}$$

From Dehnen (1984)



Dense gas ($\rho = 3 \text{ kg/m}^3$)

Release Type



Biological Agents – Multiple particle sizes, gravitational settling, UV decay, dry powders and bio-slurries including evaporation of droplets with time

Zajic, D., M. Nelson, M. Williams, and M. Brown, 2010:

Description and Evaluation of the QUIC Droplet Spray Scheme -

Droplet Evaporation and Surface Deposition, 16th AMS Conf. Appl. Air Poll. Met., Atlanta.



Chemical Warfare Agents – Two-phase flow capable, i.e., we track both the liquid droplet and the evaporated gas; multi-droplet size capable

Williams, M., M. Nelson, and M. Brown, 2009: QUIC-PLUME Theory Guide, Draft, 45 pp.



Release Type

Radiological Dispersal Devices

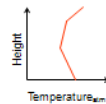


QUIC scheme based on:

Boughton, B. A. and J. M. DeLaurentis, "An Integral Model of Plume Rise from High Explosive Detonations," SAND-86-2553C.

Initial Conditions

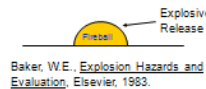
- Layered atmosphere (i.e., temperature gradients)



- Hemispherical Source

$$T_{plume}(t_0) = T_{fire}$$

$$r_{fire} = 3(HE_{mass} \frac{\rho_{atm}}{\rho_{fire}})^{1/3}$$



Force Estimation



$$F_B = g \frac{\theta_p(t) - \theta_{atm}}{\theta_{atm}}$$

Note: θ is the potential temperature.

Temperature Evolution

$$\theta_p(t) = \theta_p(t-1) - F_{entrain} \cdot (\theta_p(t-1) - \theta_{atm})$$

entrainment fraction

$$F_{entrain} = \frac{vol(t) - vol(t-1)}{vol(t)}$$



Mean Upward Motion Due To Buoyancy

$$\Delta z_{buoy} = \frac{1}{2} F_B \Delta t^2 + \bar{w}_B \Delta t$$

$$\text{where } \bar{w}_B(t) = (vol_{t-1} / vol_t) \cdot \bar{w}_B(t-1)$$

$$\text{and } \bar{w}_B(0) = F_B \Delta t$$



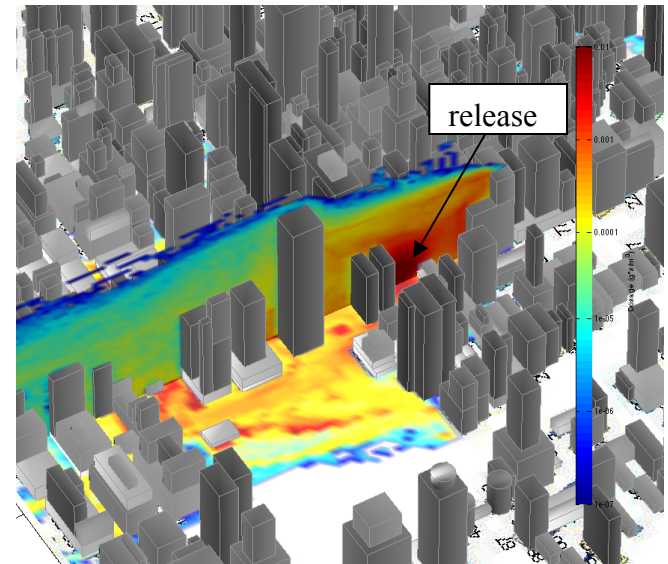
Δz_{buoy} applied to particles

Buoyancy-Induced Turbulence

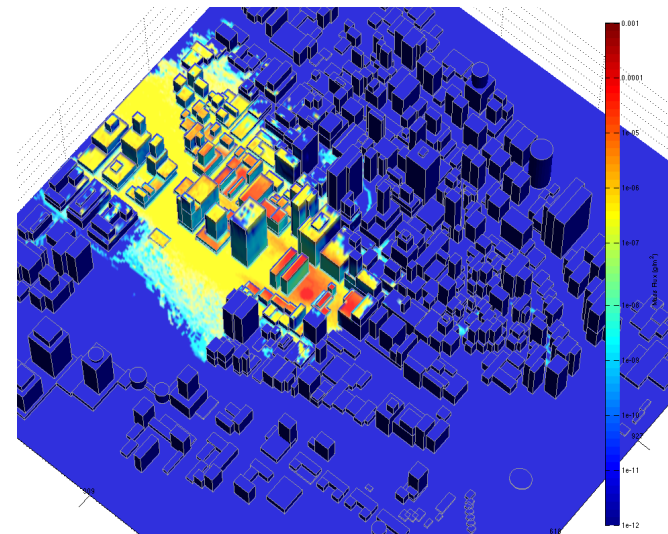
$$w'_B(t + \Delta t) = e^{-\frac{\Delta t}{\tau_{scale}}} \cdot w'_B(t) + (1 - e^{-\frac{\Delta t}{\tau_{scale}}}) \cdot w'_{B_ran}$$

$$\text{where } \tau_{scale} = \frac{\min(\Delta z, \sigma_{wB})}{\bar{w}_B + F_B \Delta t} \text{ and } \sigma_{wB} = \sigma_{wB} = 0.2 \cdot (\bar{w}_B + F_B \Delta t)$$

Drawn from Gaussian distribution with std dev σ_{wB}



Airborne Dosage



Deposition

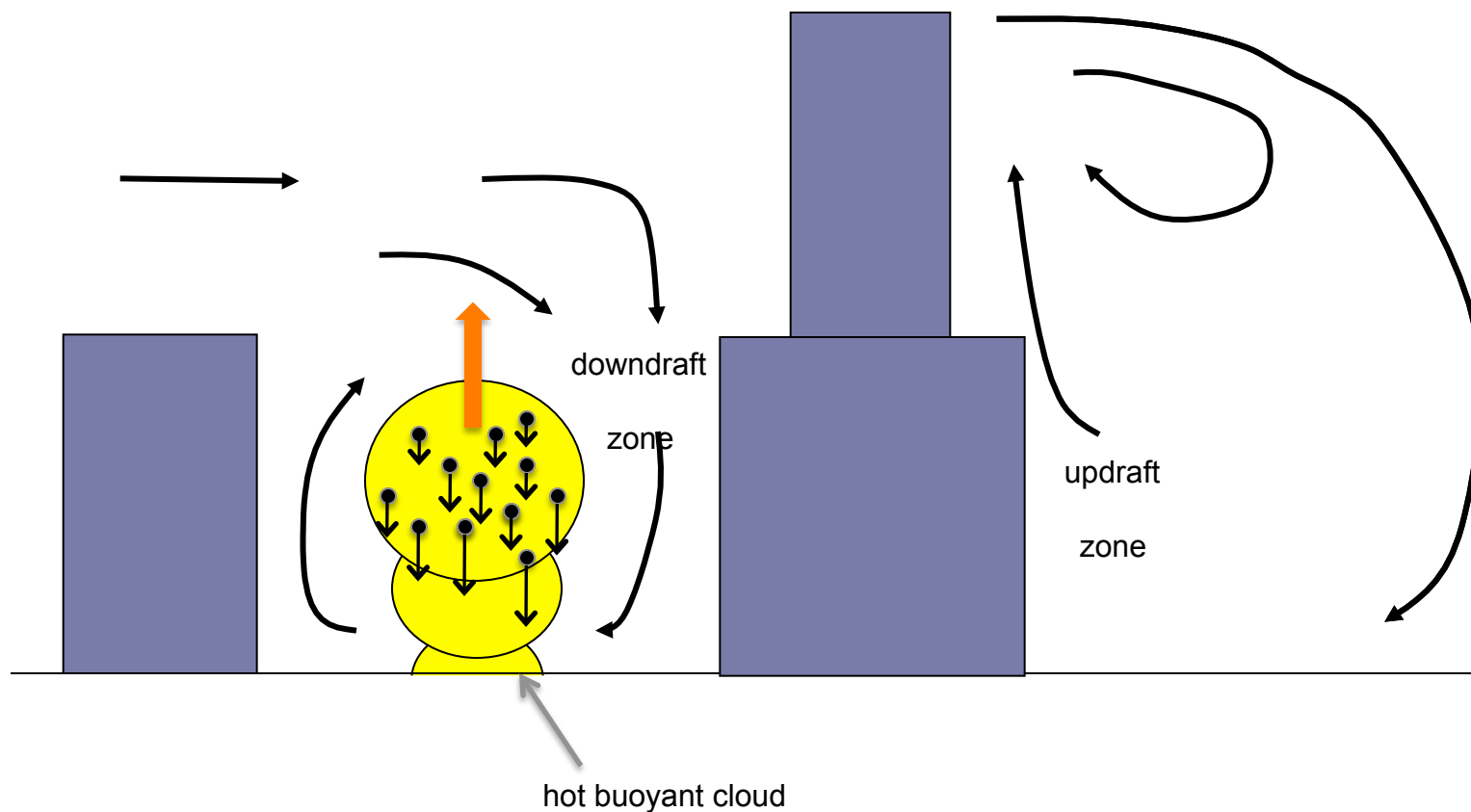
QUIC RDD Scheme

Accounts for the interaction of:

- **buoyant explosive rise**
- **size-dependent gravitational settling**
- **updrafts and downdrafts created by buildings**

QUIC RDD Scheme

Interaction of buoyant updraft, particle settling, and building-induced winds



QUIC's Niche

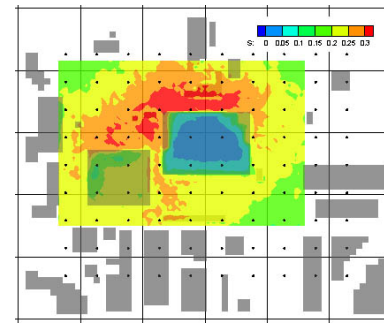
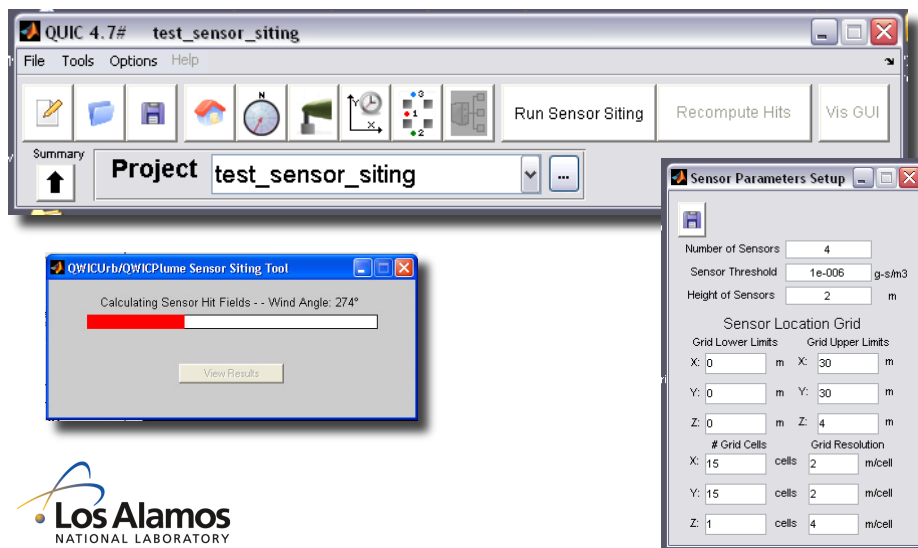
1. **Urban dispersion with buildings**
2. **Relatively fast**
3. **Chemical, biological, and radiological agents**
4. **Advanced users**

QUIC's Niche

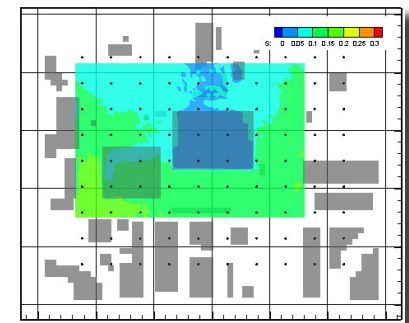
1. **Urban dispersion with buildings**
2. **Relatively fast**
3. **Chemical, biological, and radiological agents**
4. **Advanced users**
5. **Applications where many simulations must be performed or rapid feedback is required**

Intended Uses

1. Vulnerability assessments
2. Table-top training exercises
3. “What if” impact studies
4. Interpretation of urban field measurements
5. Sensor siting at facilities and special events



Hit probability map for 1st collector



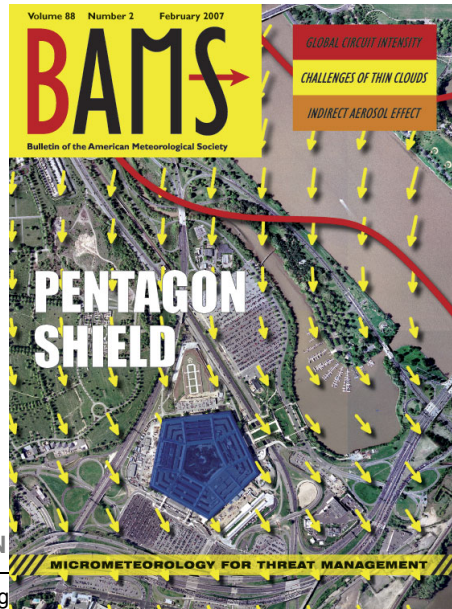
Hit probability map for 2nd collector

Intended Uses

1. Vulnerability assessments
2. Table-top training exercises
3. “What if” impact studies
4. Interpretation of urban field measurements
5. Sensor siting at facilities and special events
6. Operational systems

NCAR Project:

Assimilates lidar-
derived winds



Intended Uses

1. **Vulnerability assessments**
2. **Table-top training exercises**
3. **“What if” impact studies**
4. **Interpretation of urban field measurements**
5. **Sensor siting at facilities and special events**
6. **Operational systems**
7. **Emergency responder guidelines**
8. **Outdoor-to-indoor infiltration**

MCNP – Monte Carlo N - Particle

- 3D Monte Carlo many particle transport
- Large energy range (eV – 100s of GeV)
- ~400 Man-years of development
- ~350K lines of code
- 10K+ users world wide
- Parallel (MPI and omp)
- PC, Mac, Linux, Unix, Sun support
- Substantial V&V
- ~15K reference citations
- Export controlled+
 - Big deal, limits use in universities

MCNP contains a lot of physics

■ Incorporates other codes as libraries:

- LAHET (High Energy transport)
LANL
- CEM & LAQGSM (High energy transport) LANL
- CINDER (Unstable Nuclei Database) LANL
- ITS (Electron Transport)
SNL
- MARS (High Energy transport) FNAL
- HETC (High Energy transport) ORNL

■ Utilizes Nuclear and Atomic Data

- LANL, LLNL, BNL, EU, Japan

Many Mission Examples

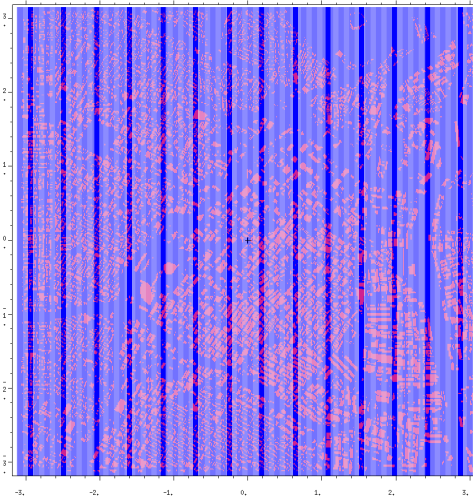
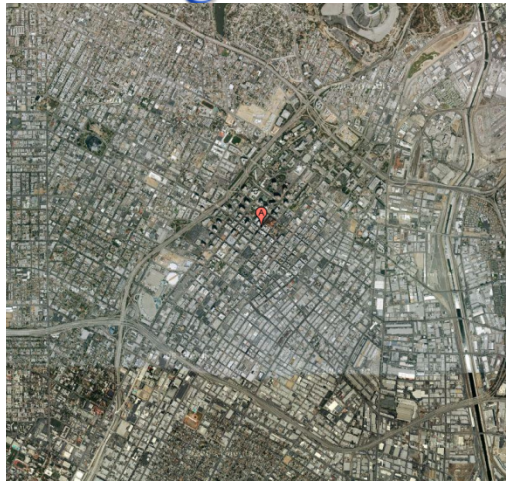
- **Stockpile Stewardship**
 - Criticality Safety
 - Radiography
- **Threat Reduction**
 - Urban Consequences
- **Non-Proliferation**
 - Reactor Actinide Inventories
 - Portal Monitors
 - Active Interrogation
- **Medical & Health Physics**
 - Shielding Design
 - Radiology, Radiation Therapy

IND Dose Effects Manageable

Input into FEMA's "Planning Guidance for Response to a Nuclear Detonation", 2nd Ed, Tammy Taylor, White House Office of Science and Technology Policy

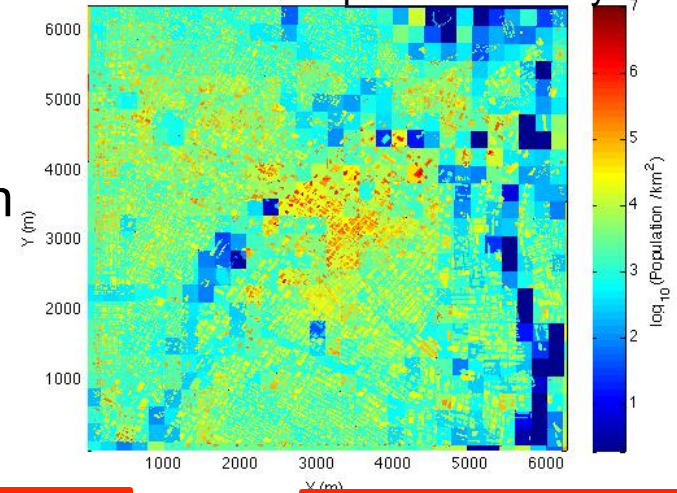
Google maps

mcnp

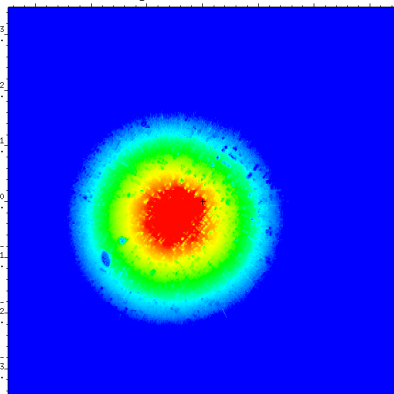


6 km

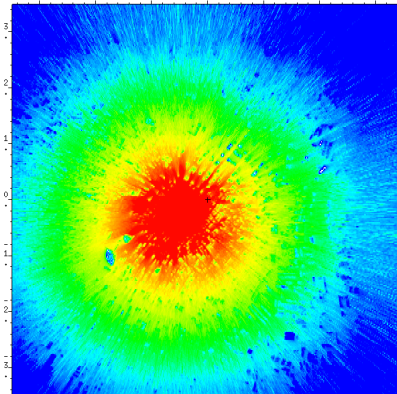
US Census Population Density



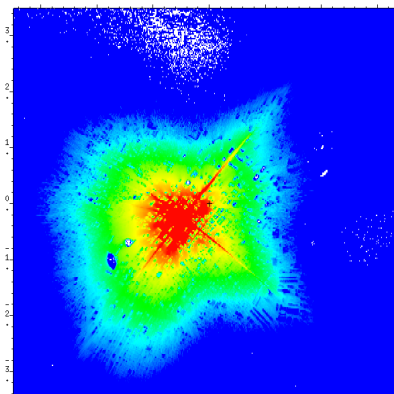
Prompt Radiation Effects - Dose



Neutron Dose (from neutron leakage)

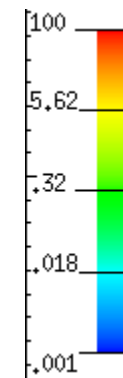


Gamma Dose (from neutron capture)

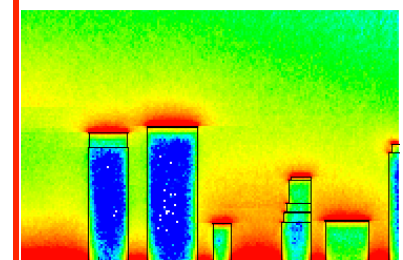


Gamma Dose (from gamma leakage)

Gy



Fallout Dose



Gamma Dose

Dose contours from a 20 kT Little Boy device in downtown LA

Operated by Los Alamos National Security, LLC for the U.S. Department of Energy's NNSA

Slide 22



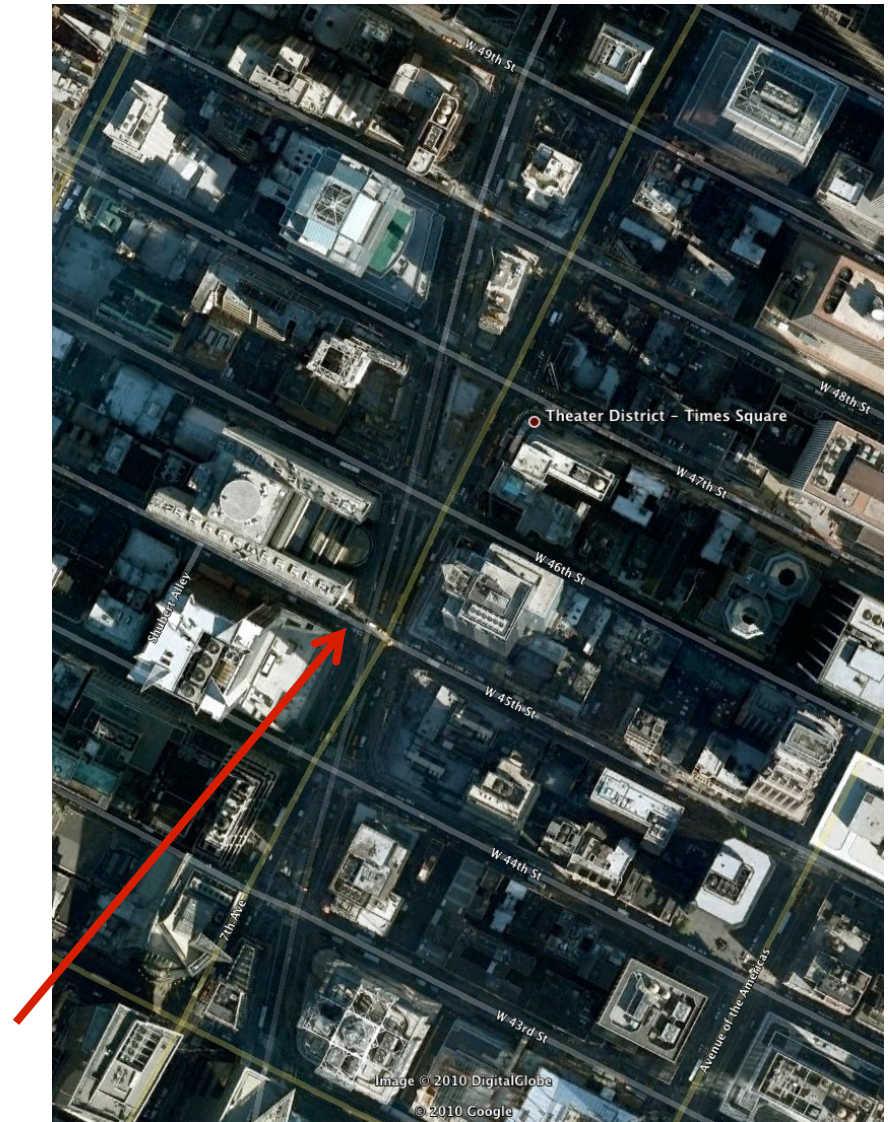
What if?

What would have happened if the Times Square bomb scare on the evening of May 1st 2010 had not only detonated but had been an RDD?

Where would the plume have gone?

What would the consequences have been?

Approximate location of the smoking Nissan Pathfinder

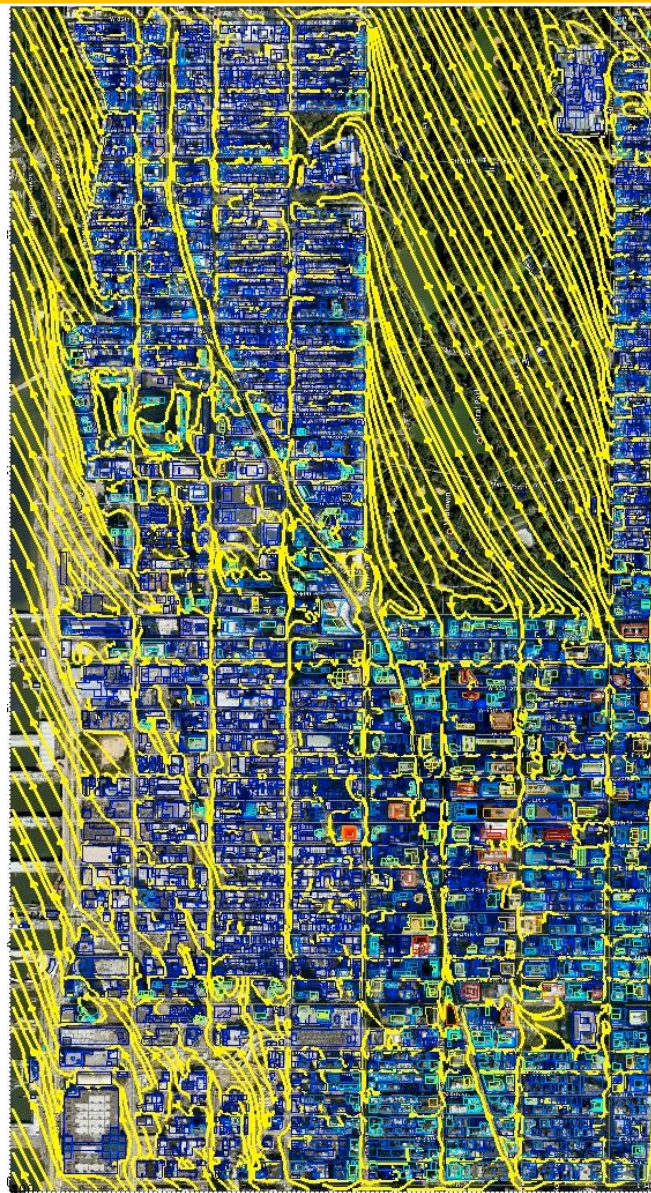


QUIC RDD SIMULATION USING UNCLASSIFIED RDD DESIGN

Simulation Parameters

- Winds in Manhattan were from the South at 6 m/s the evening of May 1st 2010
- Cloudy skies and moderate wind speeds indicate neutral thermal stability likely.
- Assume Unclassified Design RDD contained 2300 Ci of Cesium Chloride
- Assume the net energy of the explosion after escaping containment of the vehicle was the equivalent of 30 kg of TNT.
- Inner grid covers 2300 m X 4200 m at 5 m resolution (38.6 million nodes).
- Note that the domain is rotated 28 degrees CW.

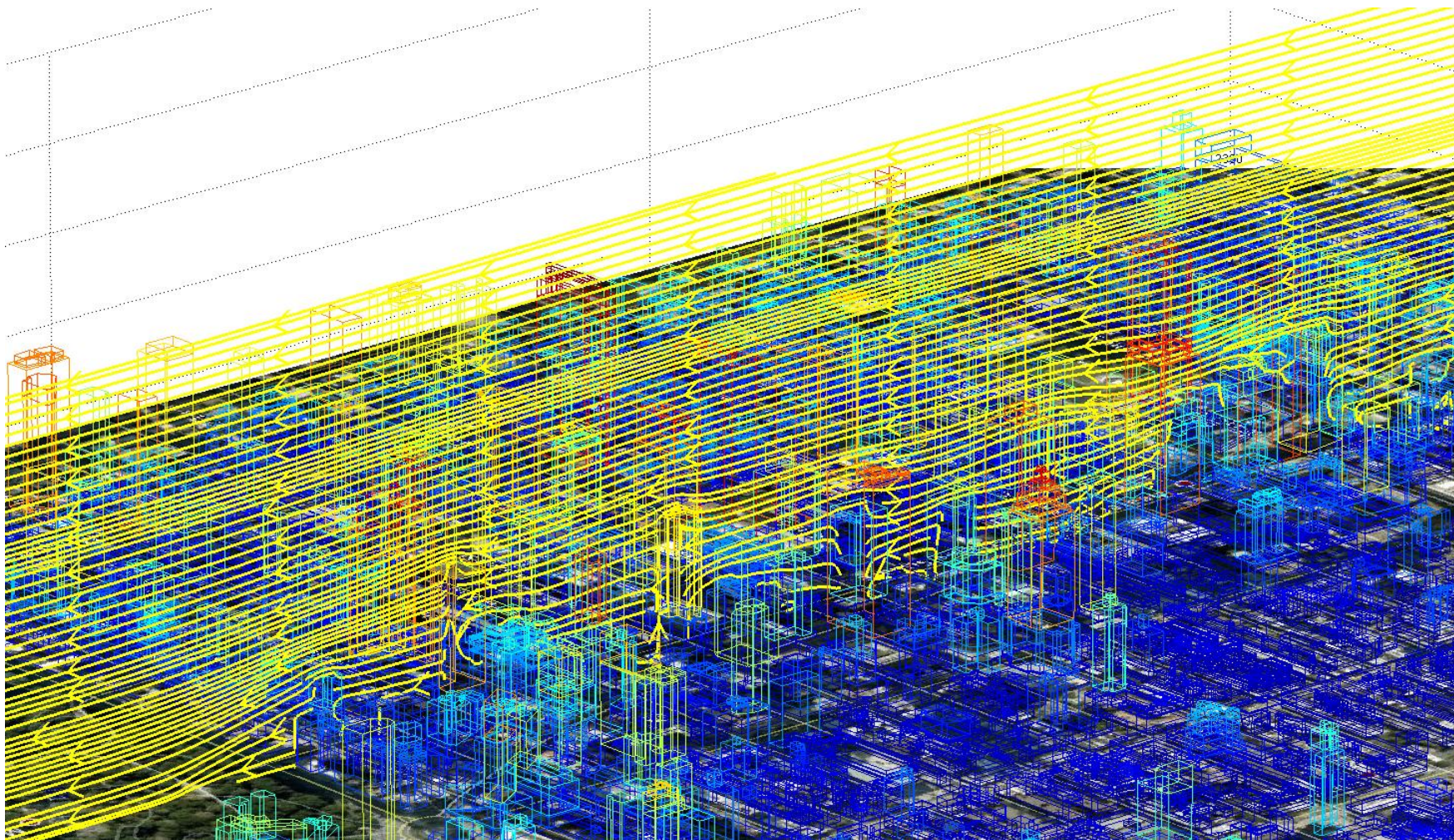
Computed Street-Level Wind Flow



UNCLASSIFIED

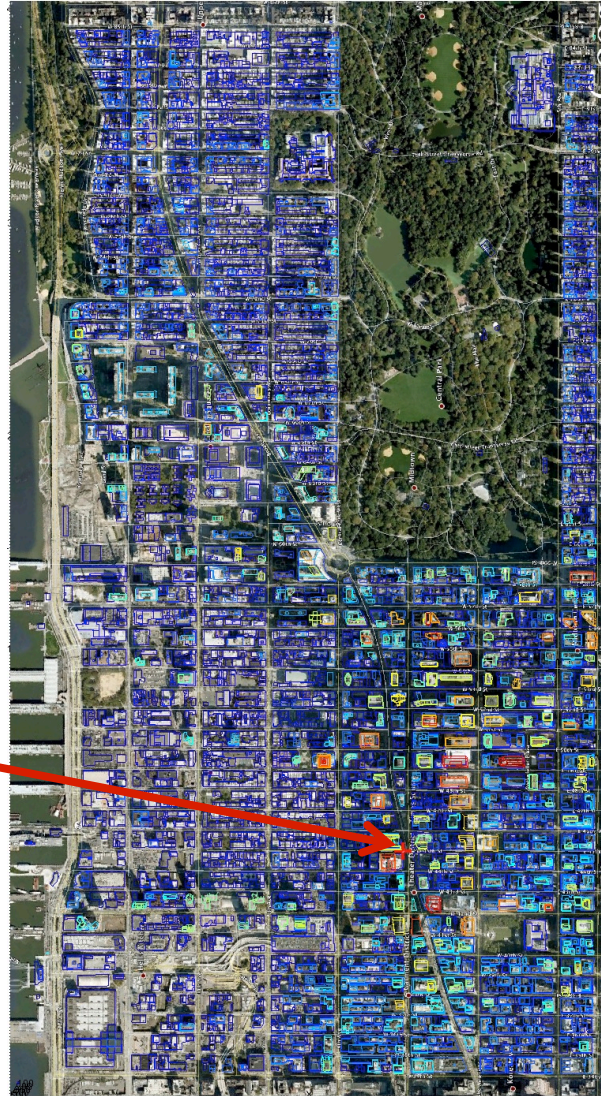
Slide 26

Computed Wind Flow Aloft

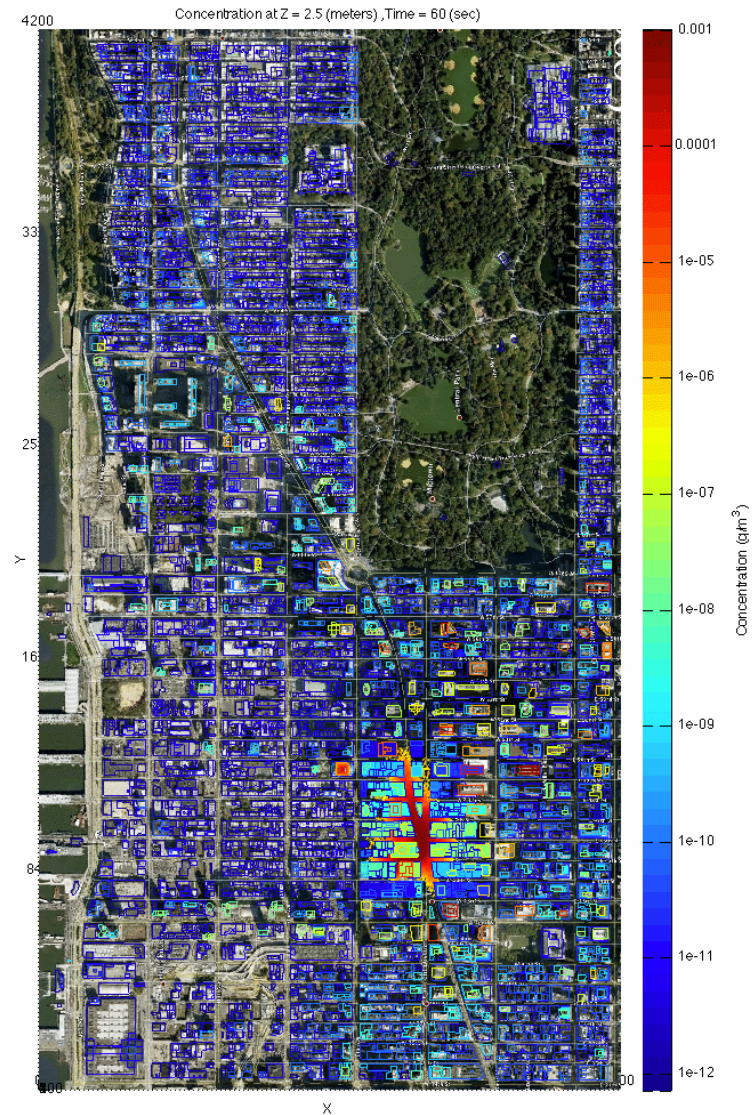


Simulation Domain

Source
Location



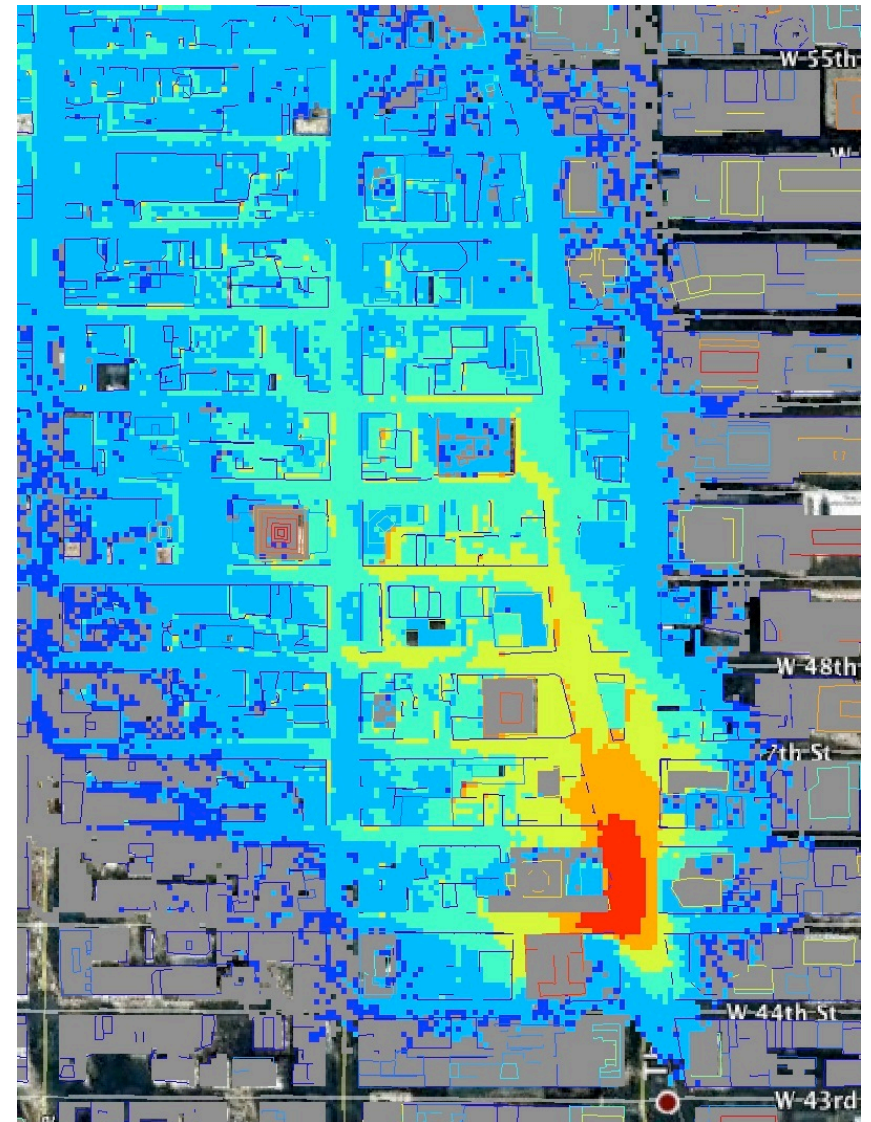
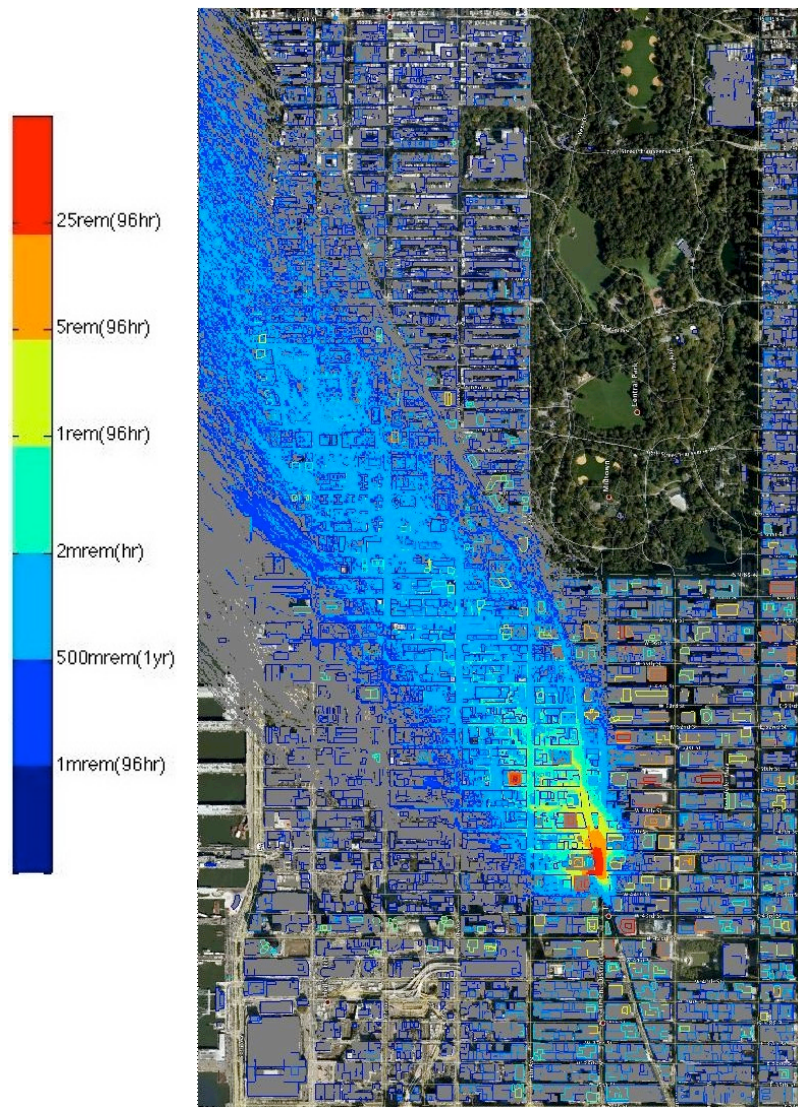
Airborne Plume— First 15 Minutes



Protective Action Guidelines (PAGs)

Exposure Level	Exposure Time	PAG description
25 rem	96 hr	EPA Emergency Personnel Limit PAG
5 rem	96 hr	Evacuation/Sheltering Upper PAG
1 rem	96 hr	Evacuation/Sheltering Lower PAG
1 mrem	96 hr	Possible Sheltering Level PAG
2mrem	1 hr	NRC Public Exclusion Zone
500 mrem	1 yr	Average Occupational Exposure

Ground Shine PAGs

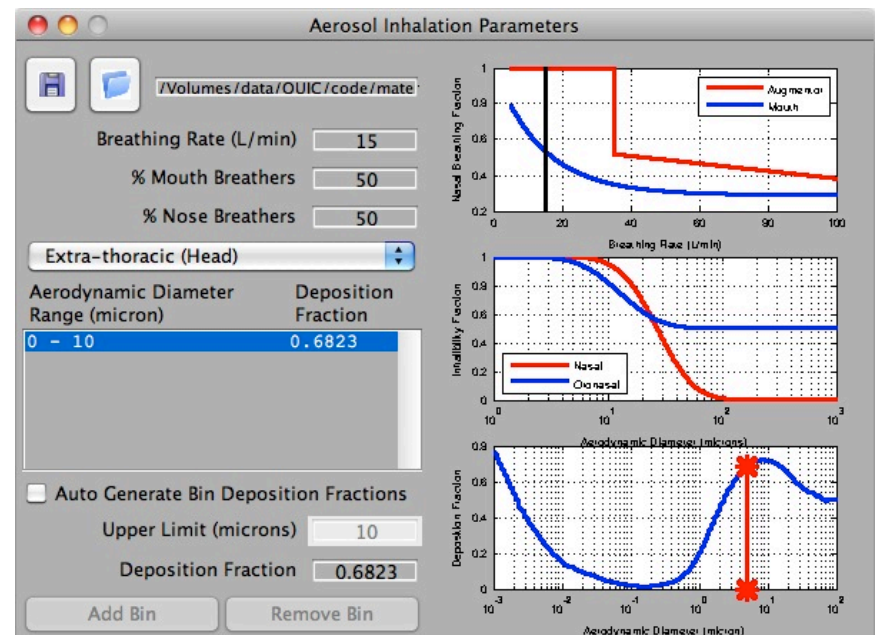


PAGs

Surface Deposition Contour Totals		
	Area (sqkm)	Total Ci
1 mrem (96 hr)	0.578	4.64
500 mrem (1 yr)	1.31	143
2 mrem (1 hr)	0.179	210
1 rem (96 hr)	0.0525	317
5 rem (96 hr)	0.0120	345
25 rem (96 hr)	0.00433	1029

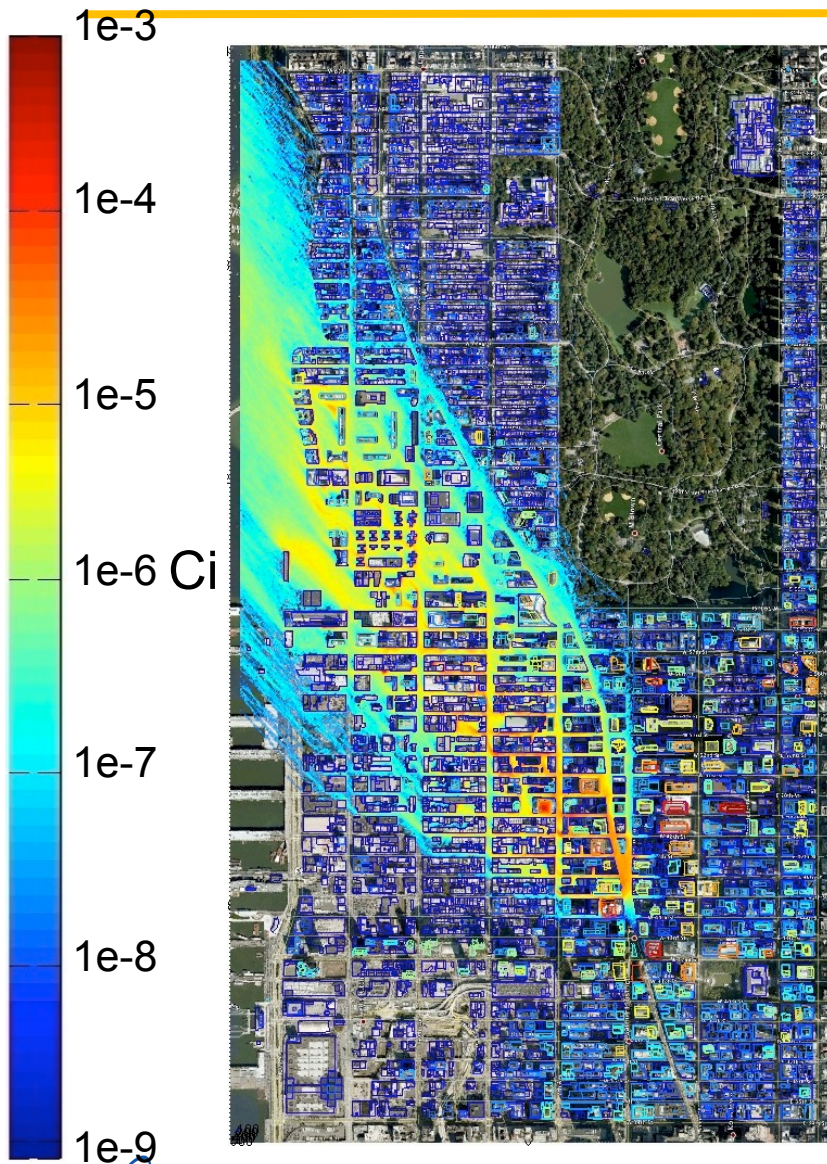
Inhaled Aerosol Dose Calculations

- Based on McClellan et al. 2007
- Accounts for deposition in:
 - Extra-thoracic (Head)
 - Tracheobronchial (Throat)
 - Pulmonary (Lungs)
- Differentiates between mouth and nose breathers



McClellan, G., J. Rodriguez, and K Millage, 2007: *Medical Modeling of Particle Size Effects for Inhalation Hazards*. 2007 CBR Consequence Assessment Modeling Conference, Charlottesville, VA, USA.

Inhaled Dose

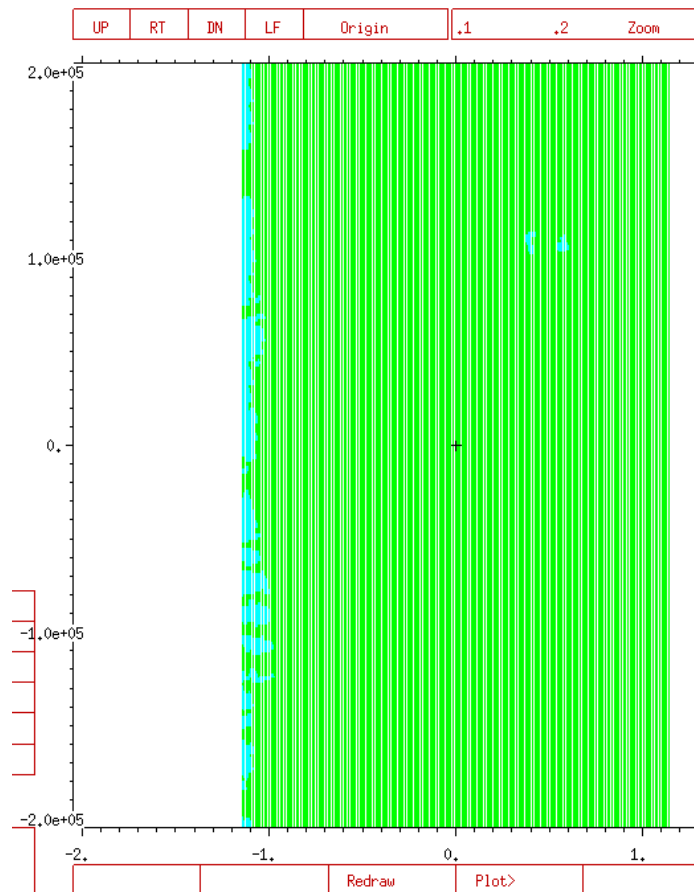


LCT01 = 2.86×10^{-3} Ci

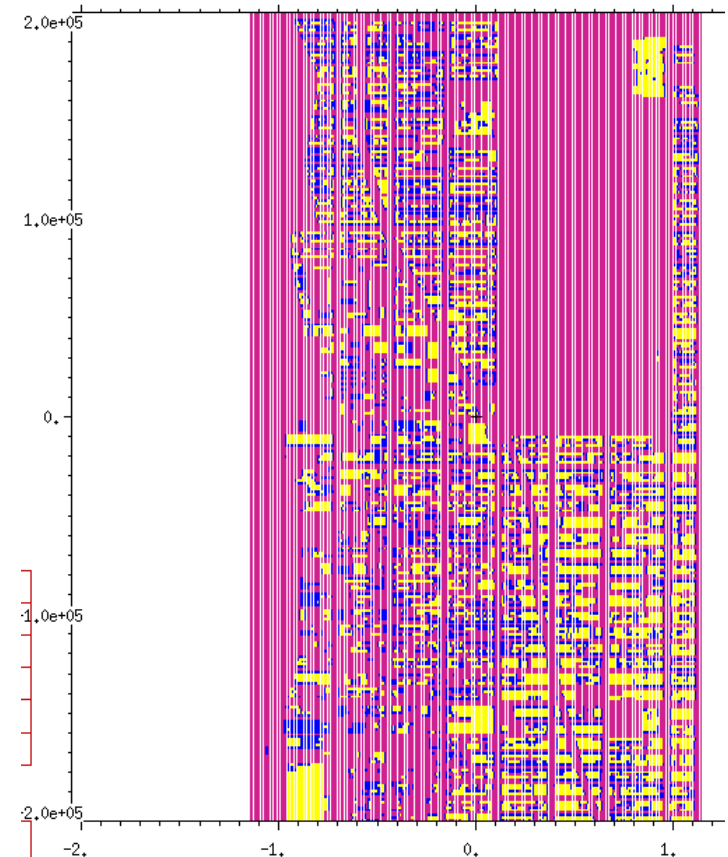
MCNP RADIATION EXPOSURE CALCULATION

MCNP - NYC Geometry

Surface Type



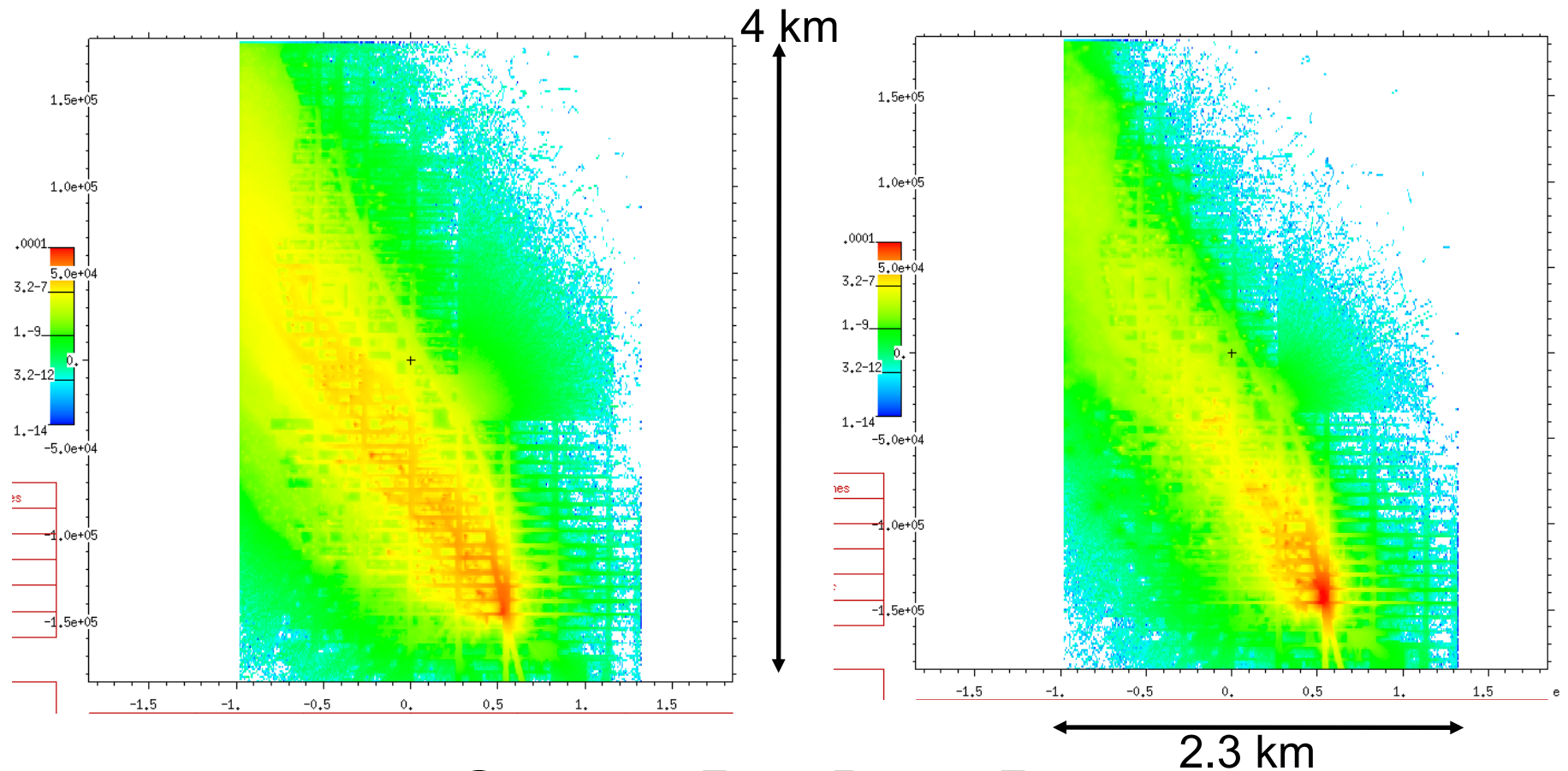
Building Height



Fallout Calculations – Horizontal

Cloud Shine

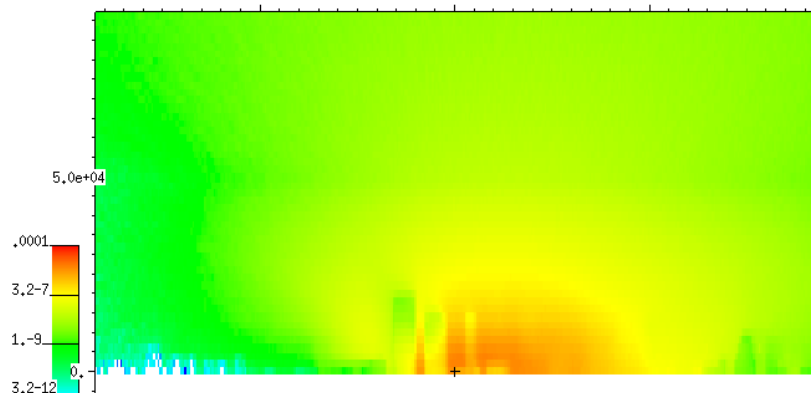
Ground Shine



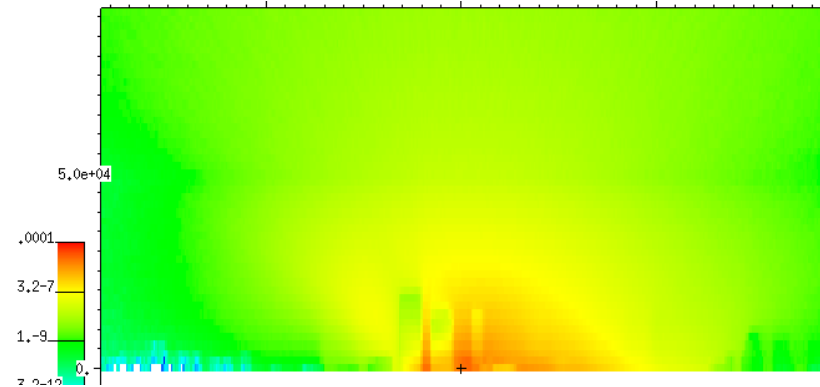
Gamma Ray Dose Rates

Fallout Calculations - Vertical

Cloud Shine



Ground Shine

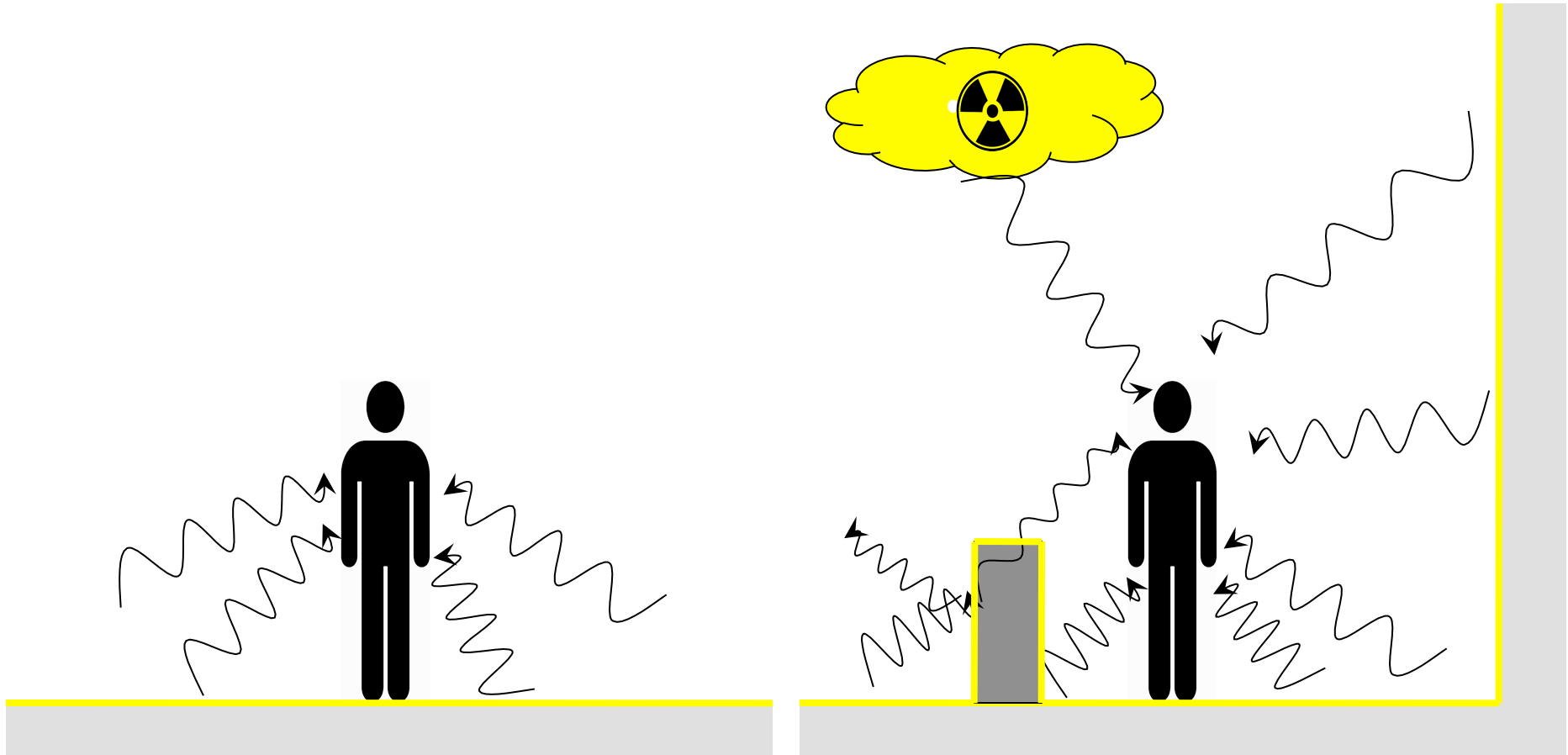


Gamma Ray Dose Rates

QUIC VS MCNP RADIOLOGICAL EXPOSURE

Radiation Transport in Urban Areas

Typical Assumptions vs. Reality

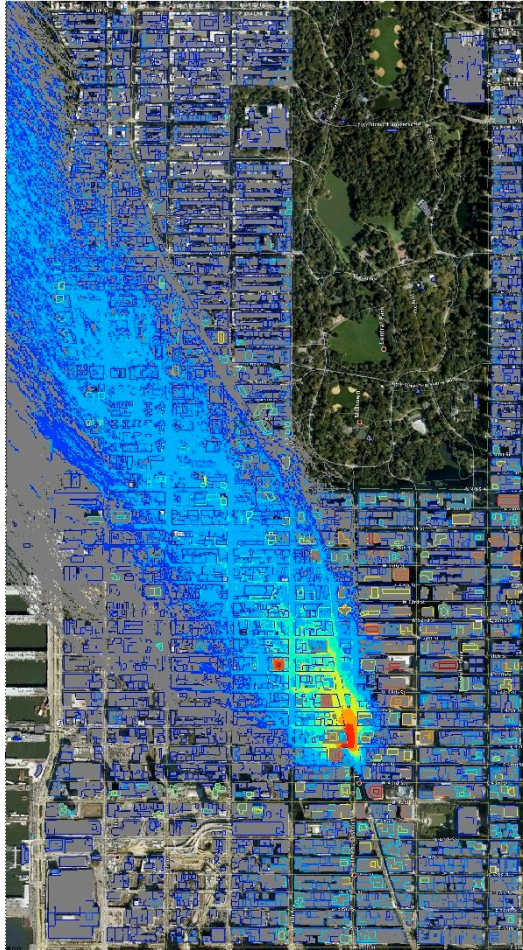


Typical Assumptions

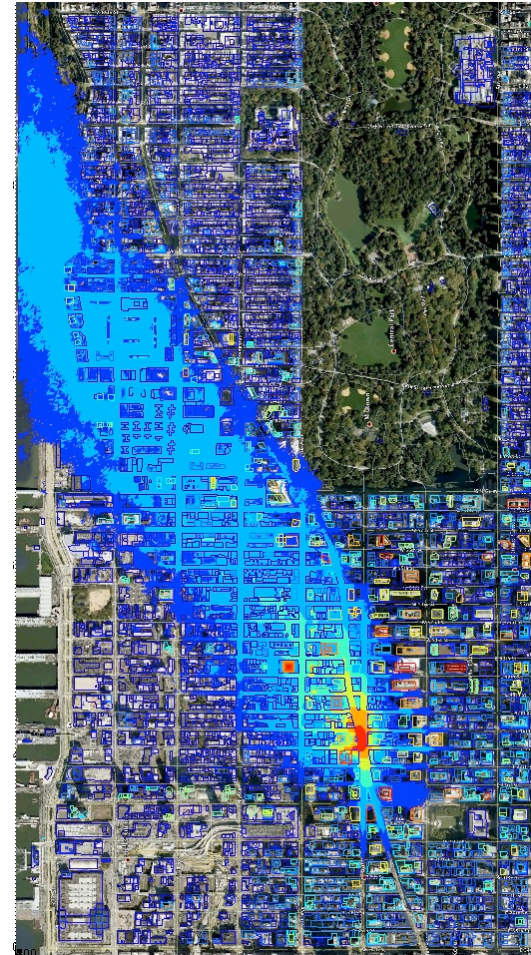
Reality

Ground Shine PAGs (Gamma Ray)

QUIC

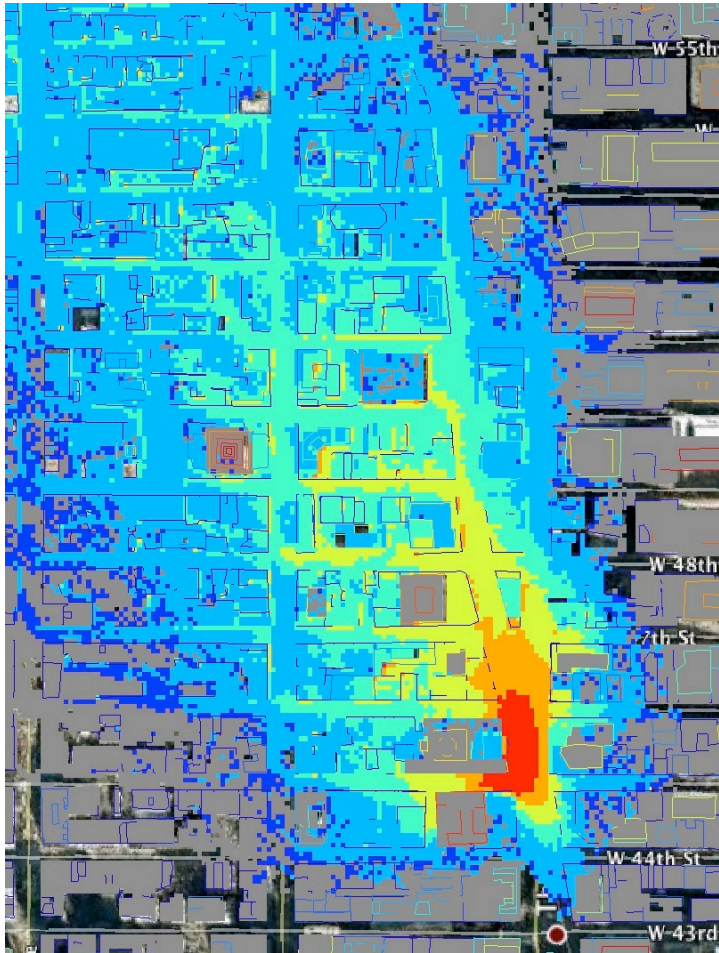


MCNP



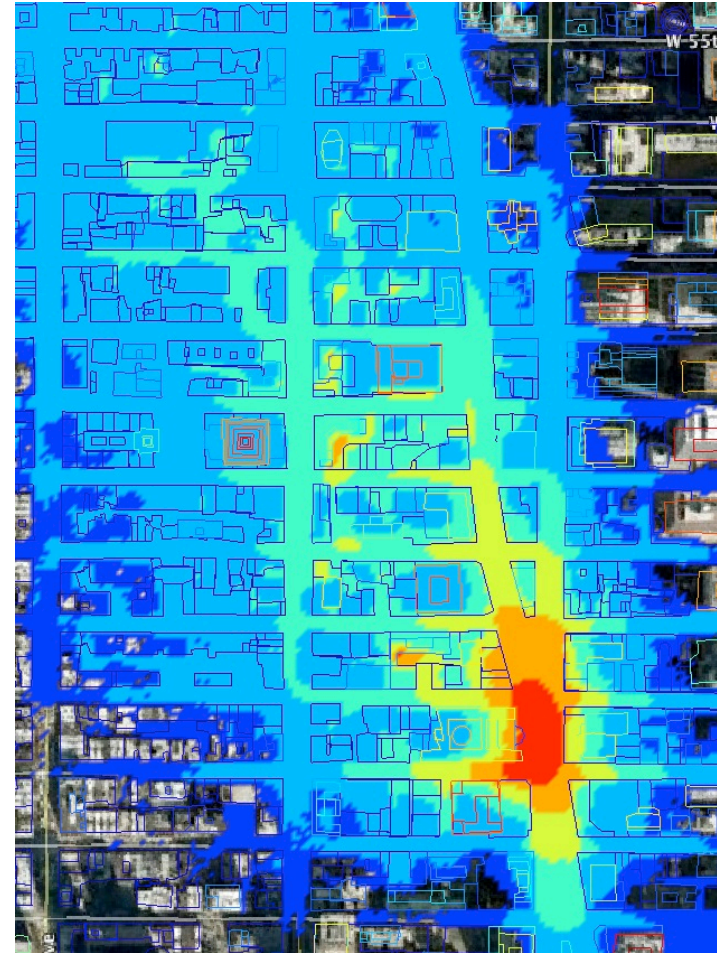
Ground Shine PAGs (Gamma Ray)

QUIC



Rooftops

MCNP



Building Interiors

Population Under PAG Contours

Exposed Population		
	QUIC	MCNP
1 mrem (96 hr)	3,451	59,133
500 mrem (1 yr)	8,784	85,026
2 mrem (1 hr)	2,967	22,122
1 rem (96 hr)	1,934	6,165
5 rem (96 hr)	762	1,003
25 rem (96 hr)	435	592

Since most people are indoors, the transmission of gamma rays into buildings makes a huge difference in the exposed populations calculations.

Conclusions

- **QUIC provides the capability of performing building-aware atmospheric dispersion simulations over neighborhood scales (1-10 km²) but its radiological exposure calculations are necessarily crude.**
- **MCNP provides the capability of incorporating many of the complexities of radiological transport in urban areas into radiological exposure calculations but does not have the ability to perform the atmospheric transport and dispersion through an urban area.**
- **Using both codes together makes it possible to make much more realistic consequence estimates following a RDD or IND attack in an urban area.**

The QUIC Dispersion Modeling System

Extra Slides



UNCLASSIFIED

Operated by Los Alamos National Security, LLC for the U.S. Department of Energy's NNSA



QUIC Capabilities

- **Biological Agents** – Multiple particle sizes, gravitational settling, UV decay, dry powders and bio-slurries including evaporation of droplets with time
- **Chemical Warfare Agents** – Two-phase flow capable, i.e., we track both the liquid droplet and the evaporated gas; multi-droplet size capable
- **Heavier-than-Air Chemical Releases** – Dense gas capability, including the effects of buildings and topography
- **Radiological Dispersal Devices** – multi-particle size, gravitational settling, high explosive mass, buoyant rise, interactions with buildings
- **Indoor Infiltration** – using building leakage factors and filtration system characteristics, QUIC can approximate the amount of material that enters a building from the outside

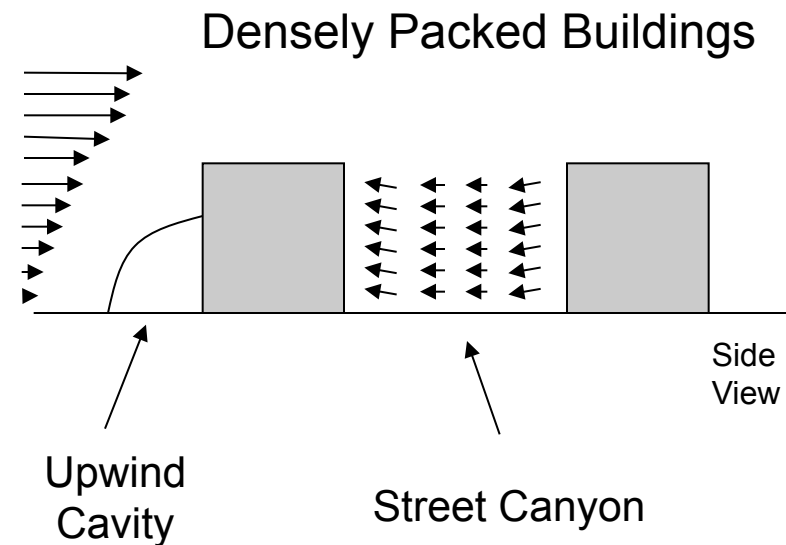
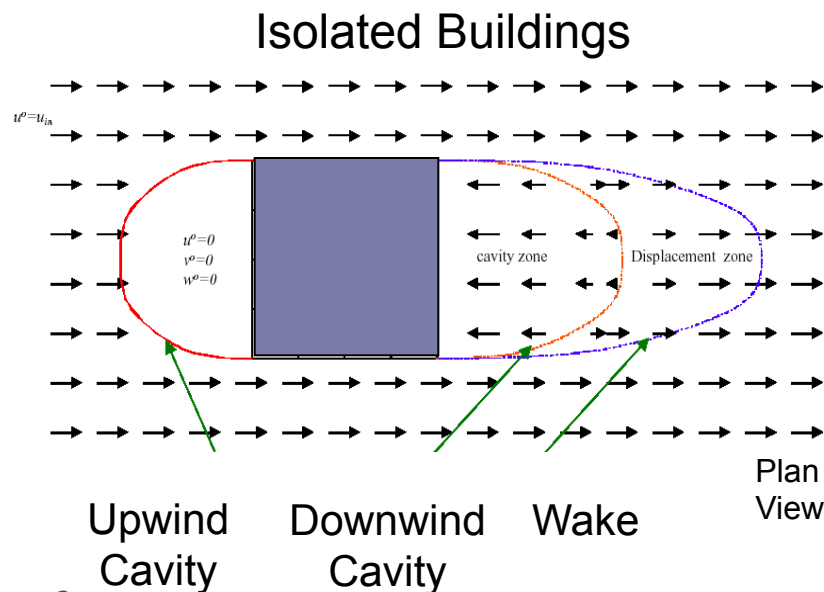
QUIC Wind Solver Methodology

Based on dissertation of Röckle (1990)

3D winds obtained from diagnostic/empirical method

Initial winds based on building spacing and geometry

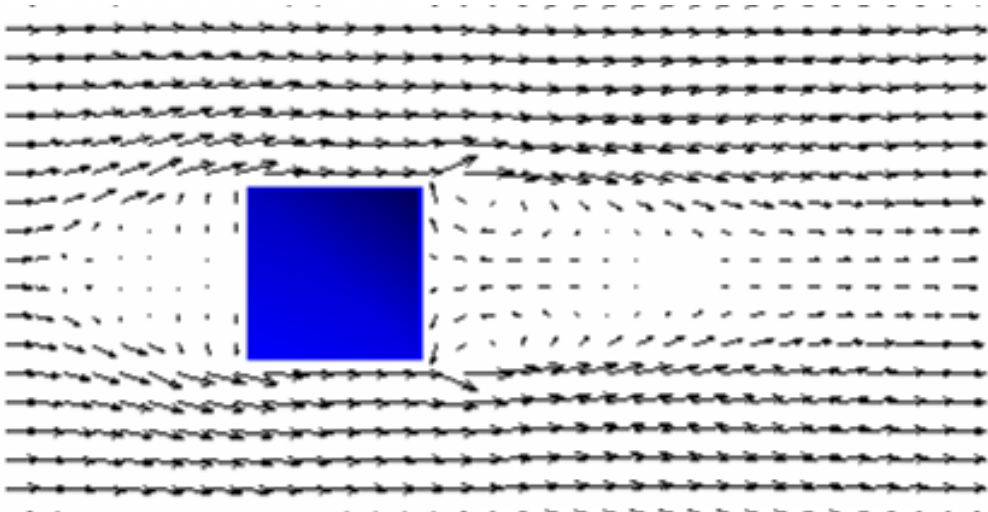
- building spacing algorithms to determine if isolated or skimming flow
- equations for cavity & wake length & shape based on H, W, L
- equations for initial velocity fields in cavities, wakes, and street canyons



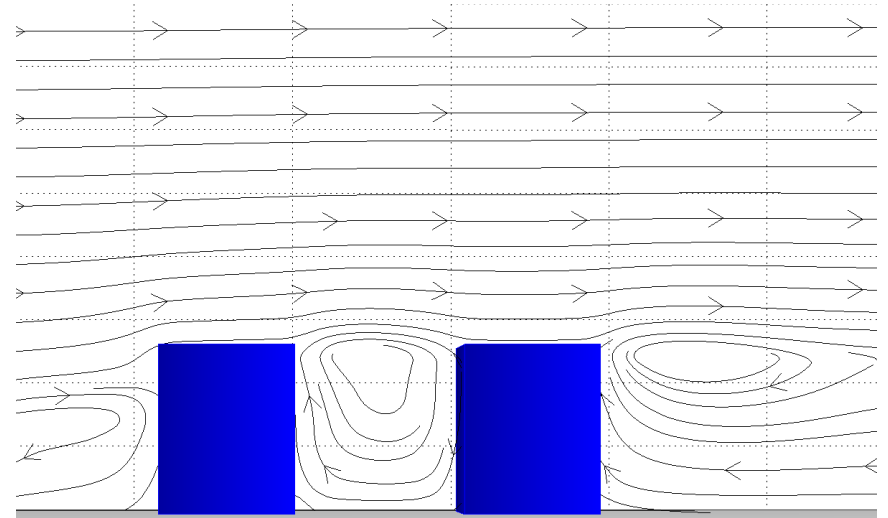
QUIC Wind Solver Methodology

Then mass conservation imposed (e.g., Sherman, 1978)

Isolated Buildings



Densely Packed Buildings



Modifications for Dense Urban Areas



- Building Parameterization Implementation Order
- Small-to-Tall Logic
- Stacked Building Cavity Region
- Reduced Cavity Length in Built-up Zones
- Street Canyon Zone Dependence on Wind Angle
- Wide-Building Cavity Length Algorithm
- High-rise Upwind Rotor Modification
- Blended intersection zones
- Wind direction dependent rooftop scheme (vortex vs. delta wing)
- Buildings at non-perpendicular angles to one another

Brown, M., A. Gowardhan, M. Nelson, M. Williams, E.R. Pardyjak, 2009: Evaluation of the QUIC wind and dispersion models using the Joint Urban 2003 Field Experiment dataset, *AMS 8th Symp. Urban Env.*, 16 pp.

Gowardhan, A., M. Brown, E.R. Pardyjak, 2009: Evaluation of a fast response pressure solver for flow around an isolated cube, *J. Env. Fluid Mech.*, published online, to appear shortly in print.

Nelson, M., B. Addepalli, F. Hornsby, A. Gowardhan, E. Pardyjak, and M. Brown: Improvements to a fast-response urban wind model, *15th AMS/AWMA Met. Aspects Air Poll.*, LA-UR-08-0206, 6 pp.

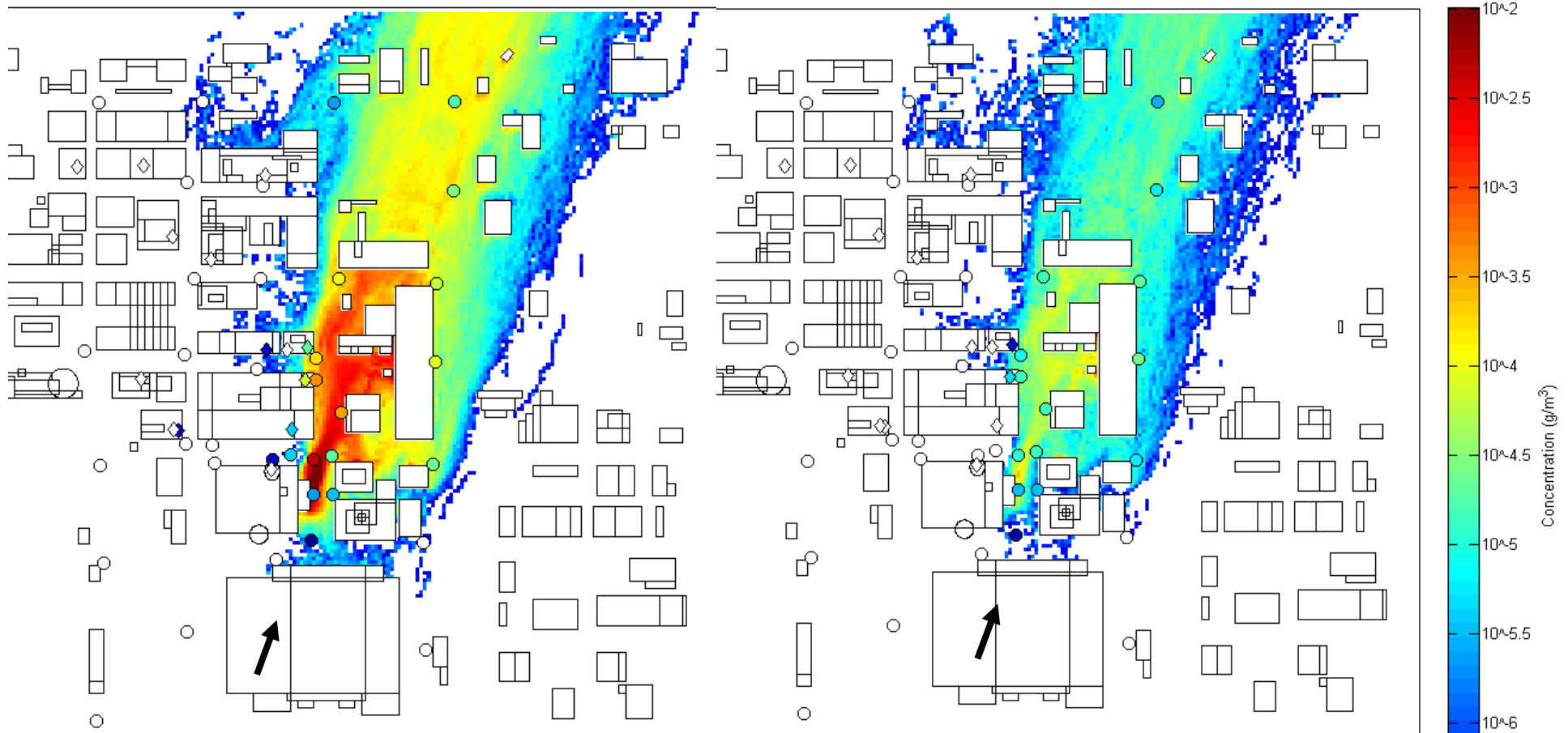
Singh, B., B. Hansen, M. Brown, E. Pardyjak, 2008: Evaluation of the QUIC-URB fast response urban wind model for a cubical building array and wide building street canyon, *Env. Fluid Mech.*, v 8, pp 281-312.

QUIC Model Evaluation – OKC Joint Urban 2003

IOP2, Release 1

10:00-10:30 CST – Source On

10:30-11:00 CST – Source Off



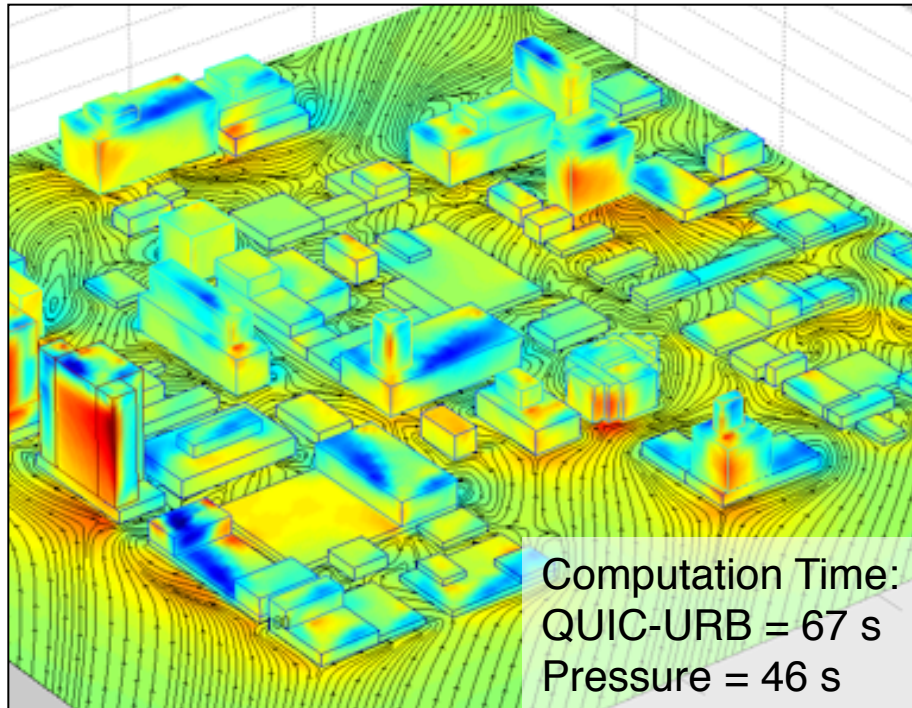
30 minute average concentrations

UNCLASSIFIED

Slide 50

QUIC Wind Solver Run Time

Streamlines & Pressure Field



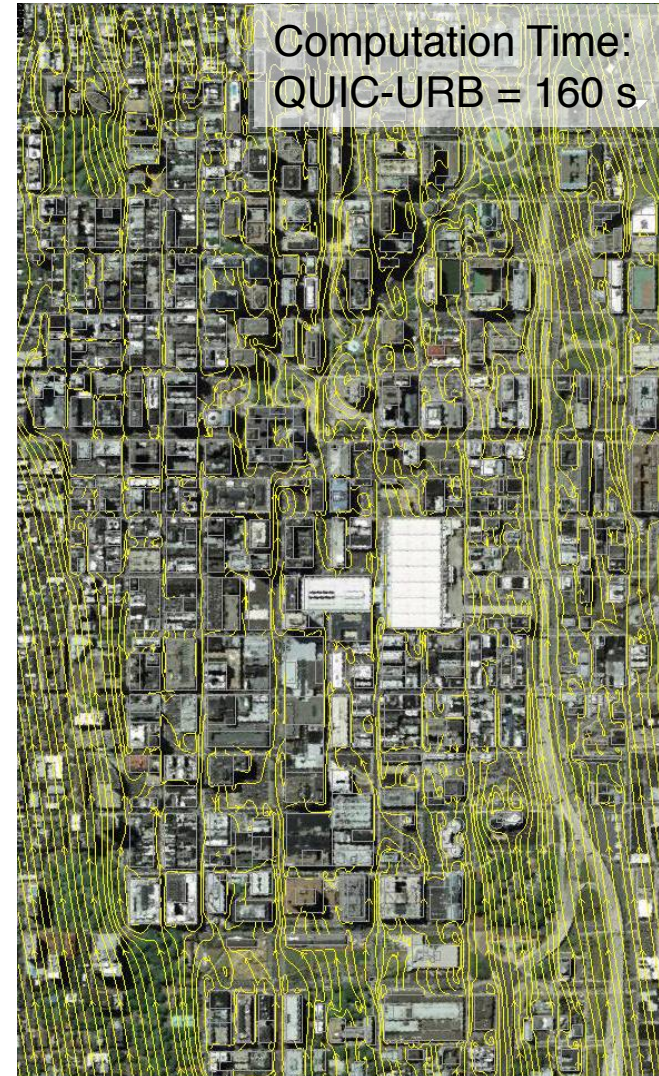
2.1 million grid cells

Mac Pro Workstation – 1 processor

First generation quad-core

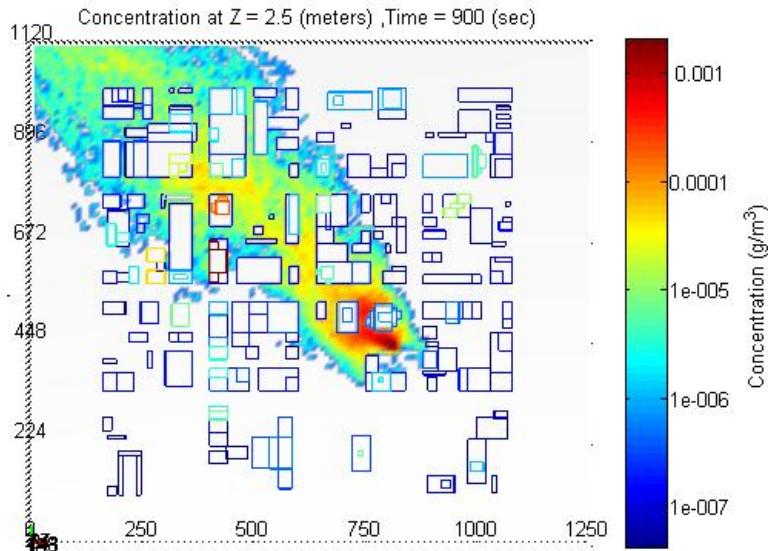
QUIC-URB

Wind Solver

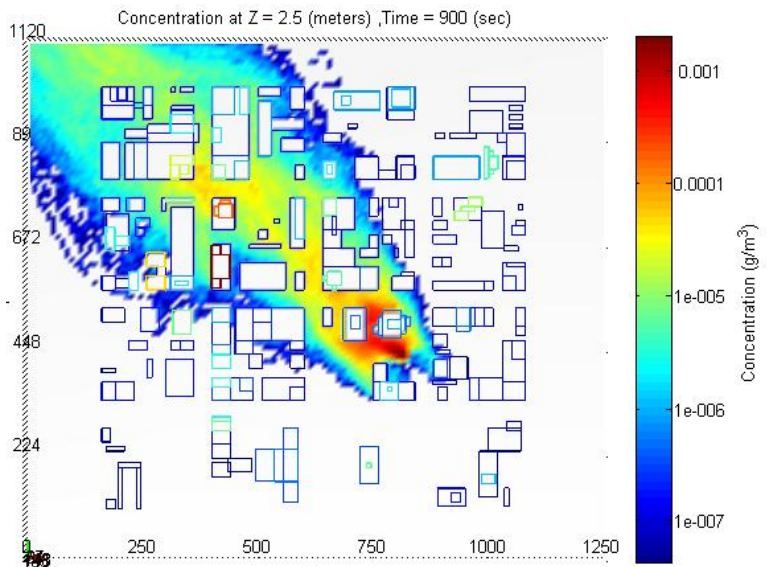


5.4 million grid cells

QUIC T&D Solver Run Time



10,000 particles
Computation Time = 1.5 min



100,000 particles
Computation Time = 14 min

Simulation Parameters:

Salt Lake City Central
Business District

Instantaneous near-sfc.
release

1.2 x 1.1 km domain

4 m/s wind speed

$\Delta t = 3$ s

<15 minute particle
clearance time

15 minute simulation

$dx=dy=10$ m, $dz=5$ m

Dell Latitude Laptop – 1 processor

4 years old!

UNCLASSIFIED

QUIC Evaluation – NYC Midtown Tracer Expt

DHS NYC Midtown Expt.

Allwine et al. (2008)

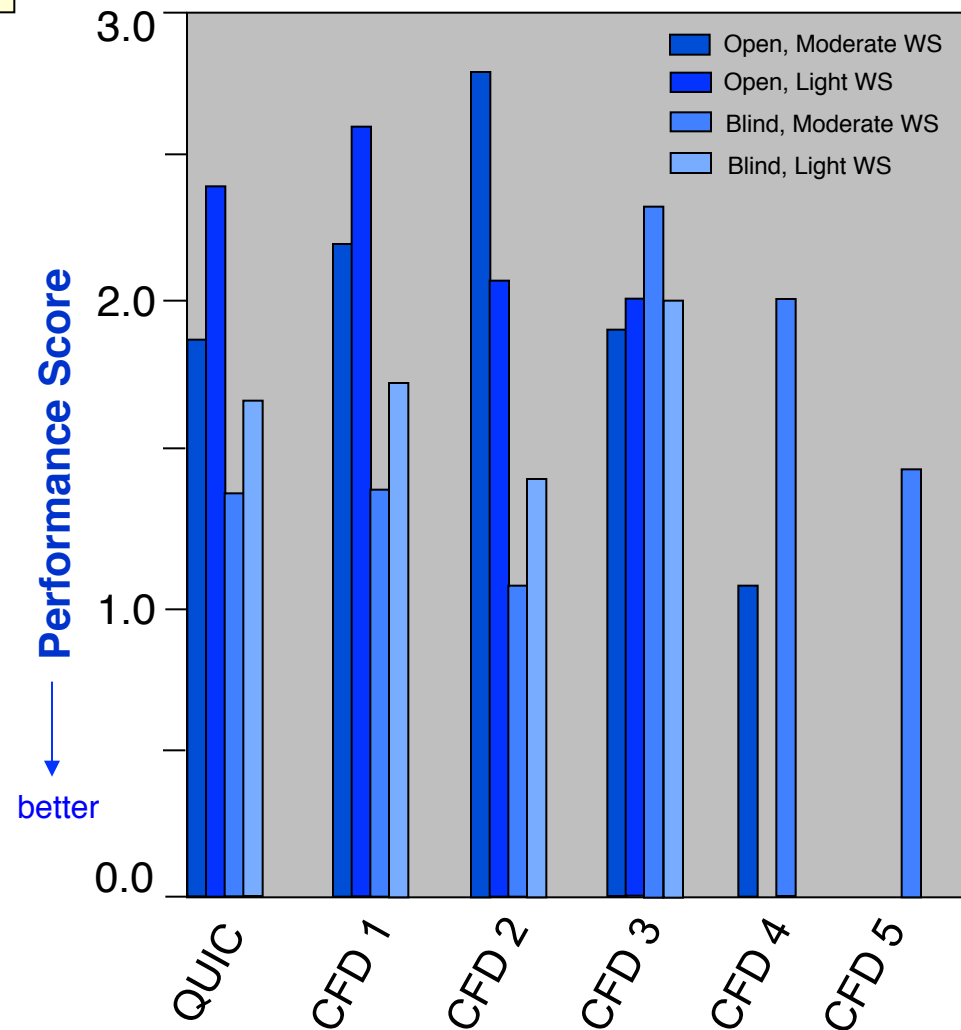
Aggregate performance score (PS) based on:

- Fraction above threshold
- Fraction within factor of 10
- Fractional bias
- Geometric mean
- Root Mean Square Error
- Geometric RMSE

PS = 0 is perfect model

$$1.1 < PS < 2.8$$

QUIC performed as well as CFD codes!



Avg. PS = 1.79
UNCLASSIFIED

QUIC Evaluation – NYC Midtown Tracer Expt

DHS NYC Midtown Expt.

Allwine et al. (2008)

Aggregate performance score (PS) based on:

- Fraction above threshold
- Fraction within factor of 10
- Fractional bias
- Geometric mean
- Root Mean Square Error
- Geometric RMSE

PS = 0 is perfect model

$1.1 < PS < 2.8$

QUIC was 2 orders of magnitude faster!

